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Assessment and Evaluation of Man-portable Robots for High-risk Professions in Urban Settings

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Abstract

There are a number of professions in which exposure to life threatening risks is part of daily routine and robots could possibly be used to avoid some of these. In fact, there are applications in which this is already done, the most prominent being bomb disposal and mine clearing. The user testing of new technology is part of achieving similar benefits for other tasks. Methods for use need to be explored, technical solutions have to be trialed, and advantages gained must be compared to the loads imposed in order to guide future development and to determine if the new tools are ready to be deployed.

This thesis has performed such feasibility tests on robots within Military Operations in Urban Terrain (MOUT). The aim has been to gain a comprehensive view of a potential user and to embed a robot amongst them in order to assess its tactical feasibility and evaluate its technical performance. An army company specialized in urban operations made up the primary user group and an iRobot Packbot Scout was the robot system in focus. Setting up the tests included identifying and modifying a number of the company's standard behaviors to include the robot. During the two tests, which lasted over a period of three and six months respectively, it was up to the users to deploy the robot as they considered appropriate.

It was found that the military rely on precise and thoroughly trained actions that can be executed with a minimum of ambiguity. Gaining similar efficiency with robots will require tactical optimization over several years. The most common application during the tests was exploration inside buildings in situations where an enemy presence was uncertain and time was not critical. Deploying the robot took more time and was less precise than traditional methods. In return it kept the soldiers out of harm's way and enabled them to decrease weapon deployment. The range of the radio link, limited video feedback, and the operator control unit were the features constraining the system's overall performance the most. Other properties, such as the robot's ruggedness, size, weight, terrain ability and endurance of the robot, on the other hand, proved to match the application. The test unit was of the opinion that robots such as the Packbot Scout would be valuable to have as a standard feature.

Four additional users groups were surveyed to examine to what extent the gained results had general validity for high-risk professionals. The most extensive of these included embedding a Packbot into a Special Weapons And Tactics (SWAT) police team for five months. It was found that the robot could be used during negotiation if upgraded with two-way audio. Further technical adaptations would also enable deployment during long term surveillance and for deploying non-lethal weapons.

Explosive Ordnance Disposal (EOD), firefighting, and Chemical Biological Radiological and Nuclear Contamination Control (CBRN) were the other groups surveyed. These were investigated by means of interviews and observations during 1-2 days. It was found that while the five professions share many demands they also have unique needs which prevents a single type of robot from being satisfactory for all of them. The tasks within EOD and fire fighting includes grasping and moving objects of up to 50-70 kg. The MOUT, CBRN and SWAT applications are less dependent on the grasping ability, but require a robot that can be easily transported and which is able to access narrows.

Sammanfattning

Det finns ett antal yrkesgrupper som dagligdags utsätts för livsfara, en del av dessa risker skulle kunna undvikas med hjälp av robotar. Faktum är att detta i viss mån redan görs, främst inom bomb- och minröjning. Användarstudier är en del av ianspråktagandet av ny teknik för att åstadkomma motsvarade vinster även för andra uppgifter. Som underlag för fortsatt utveckling och för att avgöra om de nya hjälpmedlen håller måttet för att tas i bruk måste metoder för nyttjande utforskas, tekniska lösningar utvärderas och systemens fördelar vägas mot de belastningar de medför.

Föreliggande arbete har haft som målsättningen att undersöka lämpligheten av robotar i strid i bebyggelse (SIB). Syftet har varit att skapa en övergripande bild av användaren, att implementera ett robot system, undersöka dess taktiska nytta och att genomföra teknisk utvärdering. Ett armékompani specialiserat på SIB har varit den huvudsakliga användargruppen och försöken har genomförts med en iRobot Packbot Scout. Försöksförberedelserna innefattade att identifiera ett antal av kompaniets gängse metoder som kunde modifieras till att inkludera roboten. Under försöksperioderna, som varade tre respektive sex månader, var det upp till kompaniet att utnyttja roboten så som de ansåg lämpligt.

Det visade sig att SIB bygger på exakta och noga inövade beteenden som kan utföras med ett minimum av tvetydighet. För att uppnå motsvarande effektivitet för robotnyttjande erfordras metodutveckling och optimering under flera år. Det vanligaste robotuppdraget under försöken var utforskning av byggnader under det att fiendeläget var oklart och tiden inte var kritisk. Tidsåtgången för ett robotuppdrag var högre och precisionen var sämre än för motsvarade traditionell metod. I gengäld reducerades soldaternas risk och roboten gjorde det även möjligt att minska vapen nyttjandet. Radioräckvidd, begränsad bildöverföring och brister hos styrenheten utgjorde de största begränsningarna. Andra egenskaper, så som robotens stryktålighet, storlek, vikt, terrängframkomlighet och uthållighet visade sig å andra sidan att leva upp till kraven. Försöksgruppen ansåg att en robot typ Packbot Scout vore en värdefull tillgång.

För att undersöka i vilken utsträckning de uppnådda resultaten är generell giltiga för högriskyrken undersöktes ytterligare fyra användargrupper. I den mest omfattande av dessa testades en Packbot Scout av en piketpolisgrupp under fem månader. Förhandling visade sig vara det främsta användningsområdet, givet att roboten utrustas med ljudöverföring. Den skulle även kunna komma till nytta under långtidsövervakning och för att avlossa icke dödliga vapen.

De tre övriga områden som undersöktes var bombröjning (EOD), brandförsvar samt indikering av kemiska, biologisk och radioaktiva ämnen (CBRN). Dessa mindre omfattande studier byggde på intervjuer och observationer som genomfördes under 1-2 dagar. Det visade sig att även om de fem grupperna har många krav gemensamma så finns individuella behov som inte kan tillfredställas av att enbart en typ av robot. Inom bombröjning och brandförsvar krävs att roboten kan plocka upp och transportera föremål som väger upp emot 50-70 kg. Inom SIB, CBRN och piketpolis finns användningsområden som inte kräver förmågan att hantera objekt, däremot så ställs krav på att roboten är lätt att transportera och att den kan komma åt trånga utrymmen.

Acknowledgements

To be frank I must admit that I had never even come close to considering commencing a PhD before the military staff department selected me as a candidate. My previous position dealt with Air Force acquisition at the military headquarters where the main tasks of my co-worker Oscar Hull and I were to keep track of the complete funding for Air Force material procurement and to file reports of the acquisition progress to the Department of Defence. Being an Army Lieutenant, and most probably the youngest officer ever employed in such a position, I hardly had the most suitable background. There are stories to be told about that period and I am bringing it up here only to send my thanks to Oscar and others at KRI MTRL for watching out for me so that I made it out with a record clear enough to enable a continued military carrier (I probably deserved to be fired together with the person responsible for suggesting that I apply). Returning even further back in time, I would like to mention Pär-Åke Anderskrans and Johan Wallström (then both were at the Swedish Defence Material Administration) who were the ones foresighted enough to suggest Unmanned Ground Vehicles as a topic for the military PhD program. Since then Johan, as a member of Research and Development Section 17/23, has accompanied the project. Johan, it has been a pleasure working for you.

Once accepted to the PhD program, the National Defence Colleague (FHS) became my military stationing while the Royal Institute of Technology (KTH) hosted the academic studies. For my part, the twofold affiliation offered many advantages, for example if accused of absence, always being able to claim I had been working in the other office. The primary advantage, however, was having access to two supervisors, Henrik Christensen and Stefan Axberg. Henrik I would like to thank you for support, freedom, and insights in both robotics as well as how to get research projects going. Particularly I would like to acknowledge your loyalty in remaining my supervisor even after moving to Georgia Tech. Stefan, I thank you for standing with the promise you made on our first meeting. This was back in 2001, before I decided to aspire for a PhD, you said that accepting would enable me to take leaves for pursuing my alternative career in the mountains. I would also like to thank you for never hesitating in you belief in the project. Kerstin Sevrin-Eklund (KTH), thank you for taking the time to discuss the outline of my research. Charles Thorpe, thank you for hosting my visit at Carnegie Mellon University and for enabling my participation at Navlab.

Out of the all the fellow co-workers I had at FHS, there are some I particularly would like to mention: Klas Andersson who reviewed and discussed most of the results of mine and in addition has shared so many of the hardships along the academic path (Maryland, Hawaii, Yosemite, Sunset Beach, La Torche, Chamonix and Halmstad just to mention a few). Martin Norsell for your support, good advice and encouragement – I appreciated it! Joel Brynielsson (yes, the legendary Amiga hacker), you receive my deepest respects for your strict accuracy and in-depth computer knowledge which you generously share in a graspable way. Without Joel's support I would have been stuck with some despised word processor instead of proper LaTeXtypesetting.

I would like to take the opportunity to direct an apology to anybody at the Centre for Autonomous Systems (CAS) and the Computer Vision & Active Perception lab (CVAP), that has been annoyed by the rattle of military robots running up and down the corridors. I direct my gratitude to everyone who, in one way or the other, has been part of the two labs along the years (we must have had people and robots from all continents). In particular I would like to thank Patric Jensfelt for always being willing to assist when help was needed and Helge Hüttenrauch for an unexpected, but highly valued review. My gratitude also goes out to Jeanna Ayoubi and Mariann Berggren for handling all the matters that researchers are incompetent to deal with (such as administration, structure, consistency, and continuity). Of course, I also have to say a few words about Danica Kragic. The only time I addressed her for a professional reason (I wanted to use a camera I found, seemingly out of use in a pile of *published and abandoned* hardware), she literally promised to kill me if it got lost or broken. Dani thanks for the flavour added to the Swedish indifference, I enjoyed watching your show! Hugo Cornelius, Frank Lingelbach and Mikael Rosbacke, thanks for friendship, laughter and computer support (Micke and I shared office in the old CAS building and once managed to render the highest cost of all of KTH's phone extensions). Anders Green my appreciations for you taking over the paper presentation when none of the authors were there to do the job.

The military robots were by the way, not only the focus of mine. I want to direct special thanks to John Folkeson, Carl Barck-Holst, Hans Melkerud, and Andreas Hedström for providing me with robots for tests and demos. I still can not keep myself from laughing (nervously) when recalling John running Pluto (the 150 kg ATRV robot) full speed straight into a road sign in live traffic, or when Pluto, in autonomous mode, ran over Henrik's briefcase (with his Mac in it) outside the old CAS building (which by the way used to be a maternity hospital), or when Pluto nearly rolled down the stairs at the bakery test sight, or when Ingemar Lind's Saab was hit so hard at CIMI that the exhaust pipe was bent 45 degrees (Pluto, again!), or the very first Packbot trial ending up in a USD 5000 repair. As any researcher in the field will know, catastrophe rarely is far away in robotics...

If I had known that writing constitutes such a large part of research I might never have pursued (as a kid, I had to endure remedial teaching in Swedish), writing a thesis in a second language has been one of my life's hardest challenges. Fortunately I have been blessed with friends and colleagues who volunteered with assistance. I can not express how thankful I am as one of my clearest insights, once having come this far, is how hard it is to achieve something like this on ones own. In approximate order of appearance: Lotta Giornofeliche, Eric Hayman, Maria-Teresa Essen Möller, Anna Furén, Catharina Richter, Eva Karman Reinhold, Karin Åkerlund, Mike Wright, Ylva Tingström and Jens-Victor Palm – thank you all! Jennifer Heath-Andersson and Roger Reinhold, I owe you big time for your contributions on language and anthropology respectively. I would also like to direct a special thanks to the Andersson family (JVP included) for your extraordinary hospitality and joyful company.

Finally, the project would not have been possible without all the test persons. The participation of the 6th Urban Warfare Company as well as the development section of the Royal Life Guards is gratefully acknowledged. In particular I would like to mention Jonas Höglund and Anders Palm. Likewise I direct my gratitude to the Stockholm SWAT unit and Magnus Wass, Erik Borendal, Daniel Funseth, Per Ljung as well as the rest of the team working with the robot. I also want to thank hosts and participants at SkyddC, SWEDEC, the Police bomb units and the Södertörn fire department. My appreciation further goes to all the volunteers enabling the experiments, I would bring you all up in person if I had not promised to keep you anonymous.

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Contents

Chapter 1

Introduction

1.1 Background

There are a number of professions where people have to carry out tasks that put them in danger. Such tasks typically include emergency response, firefighting, search and rescue, handling hazardous substances, homeland security and military operations. Mobile robots, also referred to as Unmanned Ground Vehicles (UGVs), are already in extensive use in some of these applications. Explosives Ordnance Disposal[1] (EOD) and mine clearance operations are the most prominent of today's applications. Recently, there have been aspirations to incorporate robot technology in a number of other types of operations as well. The prospects that may be achieved can be categorized into three types:

- Replacing people in hazardous, harmful or dull tasks.
- Facilitating missions otherwise impossible for humans.
- Allowing more efficient task execution or lower cost.

The advantages of UGVs are in great demand in high-risk professions and UGV concepts that can achieve several of the mentioned advantages simultaneously will have a particular impact. The applications researchers suggest for robotics seem to have no limits. But still few UGVs have been in real[2] missions, although considerable efforts have been put into research, particularly into autonomous technology. It seems as if it will not be possible to replace humans in the short term, although there are situations and sub-tasks that may well be carried out from a safe distance (tele-operated). However, a number of issues must be resolved to enable deployment on a regular basis. Relevant niches where robots can be used successfully need to be identified and methods for deployment will have to be developed. Technical

[1]The removal, disarming, and destruction of explosives.

[2]In this thesis the term *real* specifies task execution with a genuine purpose, i.e. not for the purpose of development, testing, training or evaluation.

design needs to be refined to meet the special requirements of different groups, which requires knowledge of the users and the tasks they face. Cost efficiency requires versatile robots which can face not only multiple purposes for one particular user, but which are also adaptable for several different professions. Having the assorted end-users in the loop is the key to the process of introducing robots in new applications.

1.2 Aim

The overall intention of this project has been to investigate robot use within users groups that are subjected to high risk. Taking the user into account involved three major aspects:

1. User investigation – Identifying the users' characteristics in terms of: primary tasks, operational environment, organization, working methods, risks, main limitations and demands on gear.
2. Tactical assessment – Identifying and assessing robot applications in terms of: opinions on procurement, primary applications, ethical considerations, tactics, organization, workload, imposed drawbacks and achievable benefits.
3. Technical evaluation – Evaluating current technology as part of realistic deployment according to: requirements fulfilled and limitations and desired improvements.

The overall emphasis has been on evaluation as close to real applications as possible. Fulfilling this aspiration has entailed only taking into consideration gear that was robust and complete enough to be put in the hands of the users for testing. The aspirations of realism have also implied only carrying out the tests within the users' ordinary operational framework, i.e. in parallel with their normal tasks and demands. Choosing this approach is motivated by the belief that the validity of users' opinions concerning what could be tested in reality differs vastly from speculations regarding hypothetical concepts.

Another guideline has been to let the users alone decide when to apply the systems, i.e. to provide users with robots, train them in operation, but to let them decide how and when to deploy them. Only by letting the users govern deployment could the frequency of real deployment be investigated. Interviews, observation, and questionnaires have been the primary means for data collection.

1.3 User groups

An army company specialized in Military Operations in Urban Terrain (MOUT) was selected as the primary evaluation group. After having investigated the main characteristics and evaluated the feasibility of the robots with this military unit it was decided to validate the primary findings by investigation of a second user group – the SWAT (Special Weapons And Tactics) police. Cooperation with the MOUT and SWAT units included the implementation and long-term testing of a man-portable robot (iRobot Packbot Scout) within their everyday activities.

To examine to what extent the identified requirements were also valid for other working groups, three additional high-risk professions were surveyed: Explosive Ordnance Disposal (EOD) teams[3], firefighters, and Chemical Biological Radiological Nuclear (CBRN[4]) contamination control teams. The firefighters and EOD team already had robots in use and were therefore able to provide knowledge based on previous experience. The CBRN team was investigated regarding hypothetical use[5].

1.4 Contribution and Target groups

The scope of the present work spans from social science to technical evaluation and is intended to provide a holistic view of a group that might derive considerable benefits from UGVs. Apart from the professions that have been incorporated in the studies, a number of groups need to gain competence in the field addressed within this thesis.

If considering the fact that a number of the technical improvements that would be of great value to the users could be solved with existing technology, it becomes clear that the product development community lacks knowledge of the intended field of application. Hence, those developing the next generations of man-portable robots for high-risk applications are obvious recipients. Many of the findings could, into addition, be taken in consideration as a guideline for robots of other sizes or robot user-interfaces in general. Although most of the technical results within this thesis concern tele-operation, the description of user characteristics and many of the robot-related findings could apply to those dealing with autonomous or semi-autonomous systems as well.

Developers of military doctrines need to consider UGV technology in order to be able to adapt tactics to the benefits, as well as threats, imposed by the emerging technology. Radical changes to current operational procedures may be required. Competence in the field is also required for handling issues of procurement, maintenance, logistics, and management of human resources. The corresponding clientele within other high-risk arenas should monitor the development in the military domain in order to maintain a general awareness of the UGV field.

Finally, as this project has been directed at a holistic evaluation of UGV systems for high-risk applications, the results are expected to be of relevance to a diverse set of research communities: from psychology and cognitive science for the investigation of complex human-robot interaction; from social science for the introduction of

[3] Also known as bomb squads.
[4] Also referred to as Nuclear Biological Chemical (NBC).
[5] They had no prior robot experience nor did they undergo any robot trials.

robots as a replacement for humans; and, from the field of human rights and even philosophy for discussion about robots with lethal abilities.

1.5 Organizations Involved

This project has been a joint initiative between the Royal Institute of Technology (KTH), the National Defence College (FHS), the Defence Materiel Administration (FMV) and the Royal Life Guards (LG) of the Swedish Armed Forces. In addition, did the Stockholm SWAT unit, the Södertörn Fire Department, the CBRN Center of the Armed Forces, and the Army EOD and Demining Center (SWEDEC) participated in the study.

1.6 Outline of the Thesis

This thesis is organized with an overview of related work in Chapter 2. Thereafter, in Chapter 3, the research methodology and settings of the five user investigations are described. Chapter 4 presents the results of the primary user group (MOUT) and Chapter 5 does the same for the secondary user group (SWAT). The findings from the survey of firefighters, EOD teams and CBRN teams are given in Chapter 6. These form a base for the comparison of the five groups that is included in the same chapter, which, in addition, holds the discussion. The summary of the thesis is given in Chapter 7.

1.7 Publications

Results within this thesis have been published previously:

Christensen, H., Folkesson, J., Hedström, A., and Lundberg, C., 2004. UGV technology for urban intervention. In *Proceedings of SPIE Defence & Security Symposium*, Orlando, FL, USA.

Hedström, A., Christensen, H., and Lundberg, C., 2006. *Springer Tracts in Advanced Robotics*, volume 25, chapter A Wearable GUI for Field Robots, pages 367–376. Springer, Berlin, Germany. ISBN 9783540334521.

Lundberg, C., Barck-Holst, C., Folkeson, J., and Christensen, H. 2003. PDA interface for a field robot. In *Proceedings IEEE/RSJ International Conference on Intelligent Robots and Systems*, Las Vegas, NV, USA.

Lundberg, C. and Christensen, H. 2006. Evaluation of mapping with a tele-operated robot with video feedback. In *Proceedings of IEEE International Workshop on Robot and Human Interactive Communication*, Hatfield, United Kingdom.

Lundberg, C. and Christensen, H. 2007. Assessment of man-portable robots for law enforcement agencies. In *Proceedings of Performance Metrics for Intelligent Systems Workshop, NIST*, Washington D.C., USA.

Lundberg, C. and Christensen, H. 2007. How to break a Packbot. In *Video session of ACM/IEEE International Conference on Human-Robot Interaction*, Washington D.C., USA.

Lundberg, C., Christensen, H., and Hedström, A. 2005. The use of robots in harsh and unstructured field applications. In *Proceedings of IEEE International Workshop on Robot and Human Interactive Communication*, Nashville, TN, USA.

Lundberg, C., Christensen, H., and Reinhold, R. 2006. Long term study of a portable field robot in urban terrain. In *Proceedings of Performance Metrics for Intelligent Systems Workshop, NIST*, Gaithersburg, MD, USA.

Lundberg, C., Christensen, H., and Reinhold, R. 2007. Long-term study of a portable field robot in urban terrain. *Journal of Field Robotics*, 24(8).

Lundberg, C., Reinhold, R., and Christensen, H. 2007. Evaluation of robot deployment in real missions with the military, police, and fire brigade. In *Proceedings of SPIE Defence & Security Symposium*, Orlando, FL, USA.

Lundberg, C., Reinhold, R., and Christensen, H. 2007. Results from a long-term study of a portable field robot in urban terrain. In *Proceedings of SPIE Defence & Security Symposium*, Orlando, FL, USA.

Chapter 2

Related Work

This chapter begins with describing the main concerns when performing user studies within the area of high-risk field robotics. The primary robot applications of today are described, thereafter possible future deployment are exemplified. Finally, the importance and challenges connected to involving end-users in development are discussed.

2.1 Retrospect

The idea of using robots to complete high-risk tasks is one of the most obvious applications. Doing so has, however, not been achieved to the same extent as for example in industrial domains where robots have become an invaluable asset since the breakthrough of automation in the 1960s. The differences are not due to shortage of time for research and development on high-risk applications, since attempts to use unmanned ground vehicles in military applications date as far back as the Second World War (Chamberlain *et al.*, 1993). Instead, the reasons for the disparity must have other causes.

One explanation for the difference in progress of industrial versus field robotics is the level of structure in the operating environment. While the industrial setting can to a considerable extent be adapted to suit robots, a field-setting does not permit predefinition or consistency. Most field applications will therefore require continuous sensing of the surroundings; anticipation based on previous knowledge will not be sufficient to achieve the necessary reliability. Mobility is yet another apparent separator between the two applications. The prospects for the energy supply, communications, mobility, reliability and safety are issues posing severe challenges for moving platforms which in many applications cannot be accepted to be tethered[1].

Even if these mentioned technical issues were resolved, robot application in many high-risk applications would still not be obvious. The success of industrial

[1]Connected by cable for the supply of power or for communications.

Figure 2.1. The Remotec Andros is one of the most deployed EOD robots world wide.

robotics is to a great extent a consequence of solving exactly the same task over and over in endless cycles. In high-risk work, the tasks are, on the other hand, largely unique and may not have to be carried out very often. Still, the handling of even unlikely high-risk tasks is given substantial attention, since failing to deal with them may have severe consequences.

2.2 Field Robots of Today

Explosives Ordnance Disposal

Despite the many challenges, there are a few areas where field robots have excelled. The most common application of today, bomb removal or destruction, has been successively refined since the first attempts to modify a wheelchair and a wheelbarrow for bomb removal in Northern Ireland in the early 1970s (Birchall, 1997)(see fig. 2.1). Today this is a well-established robot niche with a selection of highly developed robots commercially available as demonstrated at the European Land Robot Trial 2006 arranged by the German Research Establishment for Applied Science (FGAN) in cooperation with the Bundeswehr (Schneider, 2007). Previous EOD robots have typically been fairly large but recently smaller versions as the Packbot EOD and Talon have started to emerge (iRobot, 2007; Foster-Miller, 2007b). The increased demand for EOD capabilities has proved so large that the US Army has launched a rapid equipping program to increase the EOD resources of the forces serving in Iraq and Afghanistan (US Army, 2007c).

Demining

While EOD tasks include targeting hazardous objects in specific locations, robotic vehicles are also deployed for wide-area clearance (Humanitarian Demining Program Office, DoD (USA), 2007). Currently this does not include detection but instead relies on mechanical neutralization[2] of the mines by rolling over, flailing, or excavating the entire section to be cleared. When carried out with tactical military purpose demining is often carried out to open a passage through minefields. When executed out of a humanitarian perspective the aim is instead to secure entire areas which may include first removing vegetation in order to target the mines; robots are available also for this task.

Law Enforcement

Today's news media occasionally report on EOD robots to be deployed within SWAT missions for non-EOD missions (Kumagai, 2002; Scheible, 2007; Metacafe, 2007). Most of these cases seem to be ad-hoc solutions in which EOD robots are used for observation and negotiation. Little research has been published on robotics for SWAT tasks (Jones *et al.*, 2002; Nguyen H., 2000; Ciccimaro *et al.*, 2003), although there are commercial products intended for the applications (Foster-Miller, 2007b; Robotics FX, 2007; Mesa-Robotics, 2007; iRobot, 2007).

Urban Search and Rescue

Rescue robotics, and especially Urban Search and Rescue (USAR), is one of the areas of field robotics currently receiving the most attention in academic research. Countermeasures against, and preparedness for, terrorist attacks as well as earthquakes have invigorated efforts to propel robot technology into application. Robots within this field can be divided into two groups; large, powerful robots for clearing up destructed infrastructure and small, highly mobile platforms that can penetrate debris to search for survivors. The latter of the two are the more common. Evaluation is performed through user studies (Hisanori, 2002; Matsuno and Tadokoro, 2004; Yanco and Drury, 2004), academic competitions (RoboCupRescue, 2007), and standardized tests such as developed by the US National Institute of Standards and Technology (Messina *et al.*, 2005). The Center for Robot Assisted Search & Rescue (CRASR) at the University of South Florida is one of the primary publishers of research within the area of field-robot user evaluation. A variety of issues have been targeted by various approaches; examples include: statistical analysis of MTBF[3] (Carlson and Murphy, 2005); systematic coding of communication in-between rescue workers to evaluate the situational awareness gained with robots (Burke *et al.*,

[2] In association with demining the term neutralization is used to specify the elimination of the explosive hazard. Mechanical neutralization, which includes either detonating or scattering the mine into small pieces, however, leaves a highly toxic waste in the ground. The waste products prevent the use of the soil for agriculture for years, hence the "neutralization" is far from complete.

[3] Mean Time Between Failure

2004); and ethnographic approaches to evaluate real deployment at the 9/11 World Trade Center crash sight (Casper, 2002).

Extraterrestrial Application

Challenges to the energy supply, communications and reliability are pushed to the limit when robots are sent into space, an application that has by now been put to the test substantially through NASA's deployment of rovers on Mars since April 2004 (Biesiadecki *et al.*, 2005; Leger *et al.*, 2005). As it takes up to 26 minutes for radio signals to travel to Mars a large proportion of the rovers' operations are carried out through primitive autonomous behaviors based on by pre-scheduled sequences of directed driving primitives such as for example "drive forward 2.34 meters, turn in place 0.3567 radians to the right, drive to location X,Y, take color pictures of the terrain at location X,Y,Z". The limited computational resources, the processor is only 20 MHz[4] made fully autonomous driving time consuming. Typical traverse rates are: 120 meters/hour blind driving, 30 meters/hour hazard avoidance in benign terrain, and roughly 10 meters/hour when relying on visual odometry (without hazard avoidance). About 25% of driving on Mars has been carried out using autonomous hazard avoidance.

Applications in Adapted Surroundings

Not all filed applications require robots that can fully cope with the complete set of demands normally encountered in a field setting. If it can be tolerated to adapt the environment of operations to suit the properties of robots, commercially feasible applications can be achieved. An example is the randomly roaming, but still efficient robotic lawnmowers roving within the boundaries of an electronic fence (Husqvarna, 2007).

2.3 Applications Under Investigation

CBRN Contamination Control and First Responders

The task of CBRN contamination control seems to be a prominent next step as sensor payloads are being refined for deployment on EOD robots already in daily use such as the Packbot, Talon and Wolverine (Smith-Detection, 2007; Foster-Miller, 2007a; Gardner *et al.*, 2006; Robotics FX, 2007; SPAWAR, 2007b).

Autonomous Driving and Convoying

Significant research is being carried out on the development of autonomous behaviors for both on- and off-road operation. Unmanned logistics convoying through

[4]RAD6K, a radiation-hard computer that can function at cold temperatures and with low power.

Figure 2.2. The winner of DARPA Grand Challenge 2005, the Stanford Vehicle based on a Diesel-powered Volkswagen Touareg R5 equipped with seven Pentium M computers, GPS, a 6 DOF (Degrees Of Freedom) inertial measurement unit, wheel speed encoding, laser range finders, a radar system, a stereo camera pair, and a monocular vision system.

hostile areas is one of the main reasons for military funding (Department of Defense (USA), 2006). The baseline for available technology is regularly demonstrated at competitions and demo-events such as the ELROB (Schneider, 2007) and DARPA Grand Challenge (DARPA (USA), 2007) (see fig. 2.2).

Security, Surveillance, Reconnaissance and Tactical Support

Surveillance, reconnaissance, and tactical support are areas of interest shared by the police, the military and the security services. The robots within the field can be divided in three categories:

- Handheld – Small platforms such as for example the Throwbot (Department of Defense (USA), 2006; Barnes *et al.*, 2005) (see fig. 2.3) which can be thrown or even catapulted into the mission area. Micro robots are limited in terms of mobility, range, power endurance, and technical complexity. Low-resolution video feedback is the only feature demonstrated so far and visual inspection is the most suitable application. Operator control units are kept compact to enable easy transport. Swarms of primitive robots working in unison are under investigation.

- Man-portable – A step up in size and weight while still feasible to be moved by one or two people, for example the Dragonrunner (Schempf *et al.*, 2003) (see fig. 2.4). This type offers the prospect of passing common obstacles such as stairs, and some of today's platforms can move with significant speed. By being more able to provide power, processor power and space, man-portable robots are able to facilitate different payloads such as sensors or arms. On

Figure 2.3. The Toughbot developed by Omnitech Robotics International, LLC for US Army Rapid Equipping Force.

available systems the operator control units are often as large and heavy as the robot itself.

- Vehicle size – Having once abandoning the man-portability constraints, the technical complexity and number of payloads can be allowed to increase. Autonomous driving and extreme mobility are the primary features under investigation within this category, as is exemplified by the Gladiator (Department of Defense (USA), 2006) (see fig. 2.5). The physical outline and supporting capacity of the targeted area decides the vehicle size and weight.

Just as for SWAT applications, the industry is offering commercial platforms, particularly for smaller or purely tele-operated robots. This is also the type most commonly used in real missions, such as reported for the Packbot EOD (Ebert and Stratton, 2005), or closest to real deployment such as the Small Unmanned Ground Vehicle (SUGV, iRobot's successor to the Packbot), which is undergoing trials with the US Army (US Army, 2007a). Systems including autonomous behaviors are, to large extent, government-financed research programs or ventures within the major military industries such as the DemoIII/MDARS of General Dynamics (Carroll *et al.*, 2005). The development for security and *home land defense* is receiving substantial investment (Department of Defense (USA), 2006) although much of the research is not published in detail, which prevents others than the participating parties form carrying out proper task assessment as a guideline for future research (Ashley, 2006). In-depth research into MOUT, including long-term deployment, has not been reported.

Figure 2.4. The extremely rugged Dragonrunner developed for the US Marin Corps with one of the more field-adapted user interfaces. In the background a Packbot EOD.

Figure 2.5. The Gladiator under development by Carnegie Mellon University in Pittsburgh for the US Marin Corps. In addition to sensors for navigation, the Gladiator is equipped with machine guns and smoke systems. It can be tele-operated up to 2-4 km.

Weaponization

Weapons deployment from robots had already been attempted with the previously mentioned World War II UGVs, although these attempts in retro perspective can be considered as desperate wartime attempts rather than technical breakthroughs (Chamberlain *et al.*, 1993).

EOD robots, on the other hand, have been used successfully to place destruction loads and firing disruptors to neutralize explosives for more than three decades (Birchall, 1997). I.e. the technology and methods exist for the safe handling of armed robots under certain circumstances. Recently, the intention has been expanded to include moving and living targets although the step from an isolated demo to beneficial deployment in a real setting will hopefully not be taken lightly (Magnuson, 2007; Kogout *et al.*, 2005; Department of Defense (USA), 2006). Issues of reliability, reliable identification, tactics and ethics need to be given very close attention.

Within the arena of unmanned aerial vehicles (UAVs), the Lockheed Martin Predator has been armed with radar-guided, air-to-ground missiles (Hellfire) that have been used against real targets in Afghanistan (National Commission on Terrorist Attacks Upon the United States, 2004; Department of Defense (USA), 2005). Although the real use of the Predator-Hellfire system represents a cornerstone for the deployment of unmanned vehicles[5], both the cost-efficiency, the reliability, and the accuracy have been questioned (Herold, 2003).

Armed robots have been explored in Sweden too. A FMV project in the early 1990s included converting a Main Battle Tank 103 to remote control (see fig. 2.6). Although all main functions, including firing the main cannon, could be tele-operated the trials were discontinued before any worthy tactical benefits had been demonstrated. Major setbacks for the approach taken within this project concerned reliability, cost efficiency and safety during testing the tank [6].

Nuclear Remediation

An early example of carrying out mobile surveillance within the arena of atomic energy is the integration of the SURBOT (White *et al.*, 1987) for mobile surveillance in a nuclear power plant; although the environment in that case can hardly be categorized as either unstructured or unknown. More challenging were the settings aimed at for the post catastrophe robot missions at Three-Mile Island, Harrisburg[7]

[5]The primary application of the Predator is still to provide intelligence, equipping it with weapons does, however, enable reaction towards targets identified. Established weapons such as torpedoes and missiles, which include technology that could qualify them as unmanned vehicles, are on the other hand intended to be weapons alone.

[6]Personal communication, October 2007, with Svantesson, C-G., National Defence College, Stockholm, Sweden.

[7]The Three-Mile Island reactor suffered a partial meltdown in 1979.

Figure 2.6. Trials to tele-operate the Swedish Main Battle Tank 103 were carried out in the early 1990s. Although all the main functions of the tank, including firing the cannon, could be executed remotely, no suitable tactical applications were identified.

and Chernobyl, Ukraine[8]. Carnegie Mellon University's Field Robotics Center built three robots for the Three-Mile Island site. Two were deployed to measure radio activity, but the reactor was sealed before the third robot, Workhorse, which cost USD 2 million (in 1979) to build, could be deployed (Kobell, 2000). After a request from Soviet officials following the Chernobyl explosion, the RedZone company was started as a spin off from Carnegie Mellon University. RedZone built the Pioneer robot for 3D-mapping and sample-taking in just nine months (see fig. 2.7). Unfortunately, it took years of discussion between the two governments before the robot could be shipped to the Ukraine. By the year 2000 the Pioneer had still not been deployed and it is unclear if it ever has been or will be (RedZone, 2007).

2.4 Non high-risk field applications

Service Robotics, Social Robotics, and Commercial Products

The arenas of toy, amusement and service robotics share many of the challenges of field robots in terms of navigation in undefined environments, user interaction, high-reliability demands, power supply, and communications. Robots as an aid for the physically impaired (Hüttenrauch and Eklundh, 2002), a robotic museum tour guide (Tomatis *et al.*, 2003), or a toy seal (Wada *et al.*, 2005) are examples of applications where robots have reached the level where they can be tested with end-users over time. In the field of service and social robotics robots are desired to have socially oriented capabilities (Fong *et al.*, 2005), an ability to relate to emotions (Gockley *et al.*, 2005) and be able to express a persona (Breazeal and Scassellati, 1999). Examples of commercially fielded applications are the robot Sony pet dog Aibo and autonomous vacuum cleaners such as the Electrolux Trilobit. Both include low-level autonomous behaviors addressing applications where failure

[8] The explosion of Chernobyl's reactor number four in 1986 is the worst nuclear accident in the history of nuclear power.

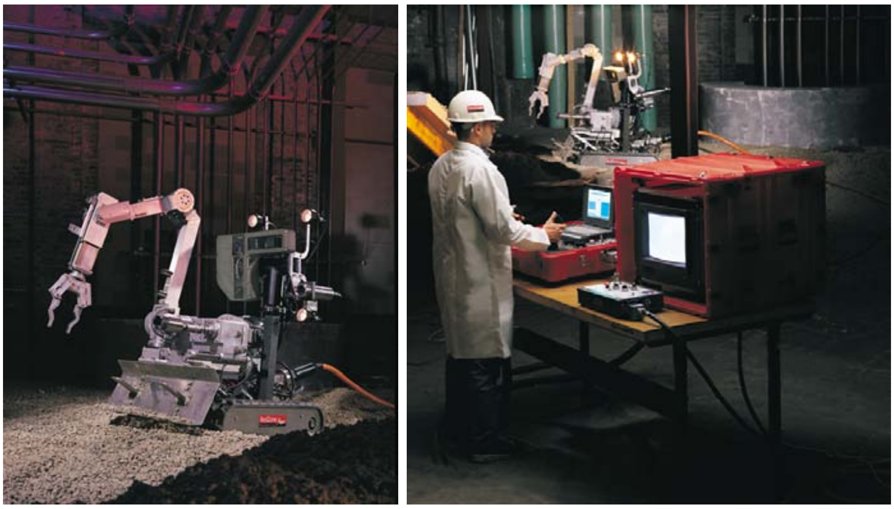

Figure 2.7. The Pioneer remote inspection system for the structural analysis of the Chernobyl Unit 4 reactor building. The system included a capability for sampling and 3D mapping. It should be noted that the Pioneer relied on a tether for communications and power supply (courtesy of RedZone) .

involves no other consequences than frustration causing commercial disadvantages. Other examples of commercial applications of primitive tele-operation (within line-of-sight) are such as construction equipment controlled from outside the vehicle instead of onboard in order to provide a better view (see fig. 2.8).

2.5 Human Robot Interaction

Autonomy vs. Tele-Operation

Although much of current research is focused on autonomy, today available autonomous technology is only sufficient for trivial field applications. Most robots in high-risk applications today are based on tele-operation. And, even as fully autonomous behaviors emerge, it is likely that users will demand the option to control or monitor the autonomous systems, particularly when performing tasks for which failure implies serious consequences. It could even be argued that tele-operation is a necessary step for technical and methodological development along with robotic evolution. Going directly to full autonomy may be a step too far in many applications; at least for legislative reasons, which have proved to be a significant challenge for peacetime UAV operation. Introducing autonomous features as support in systems primarily operated by humans could be a way to demonstrate proof of concept and to build trust, for example by using *road-following* behav-

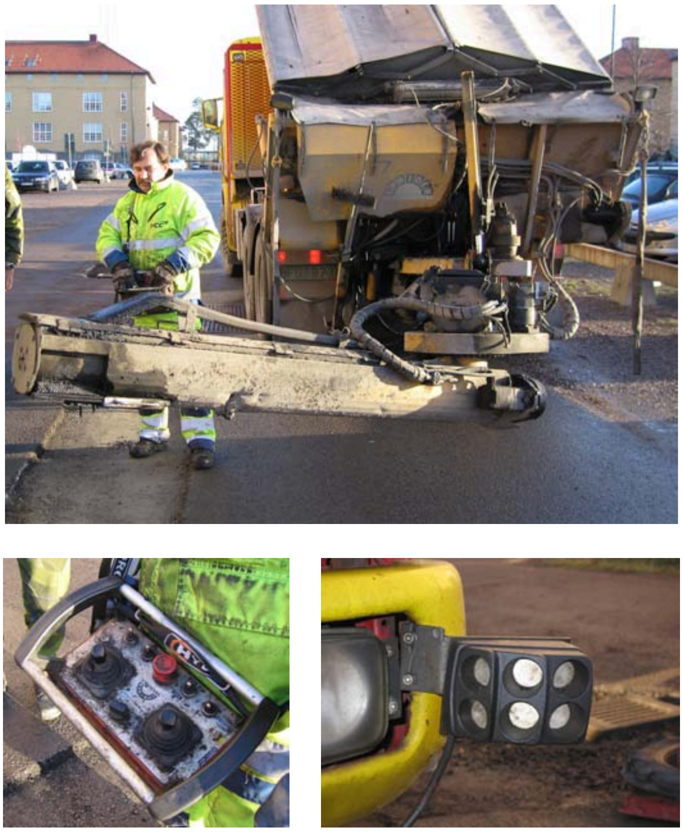

Figure 2.8. An asphalt-dispensing truck for road maintenance set up for tele-operation in order to cut down on staffing costs for a task that previously required two persons. Both the mechanical arm and the truck can be controlled by the driver with the portable and rugged user interface (below left). Ultrasonic sensors protect the system from collision (below right).

iors as a warning system in conventional vehicles[9]. The concept of collaborative systems taking advantage of humans' ability to carry out high-level reasoning and monitoring while the autonomous functions carry out the ordinary[10] (supervisory control (Sheridan, 1992)) is a concept that has been embraced in the process of fielding UAVs.

The number of operators required for the deployment of a robot is an evaluation metric (Murphy, 2004) that is frequently used by the research community as motivation for the development of autonomous behaviors (Jones and Lenser, 2006; McLurkin *et al.*, 2006). Clearly, the number of operators to a robot is an important issue in applications similar to industrial robotics, where robots have to beat the cost of human labor (for example in agriculture or forestry). A ratio of more than one robot per operator is, however, not the primary demand within high-risk professions. Before targeting the benefits of reducing man power, the robots must be able to solve the task with reasonable performance and reliability. The robot must not necessarily carry out the task as well as a human, but well enough to compensate for the various costs of a single robot.

Situational Awareness

Achieving efficient tele-operation is to a large extent a matter of attaining Situational Awareness[11] (SA) (Endsly *et al.*, 2003), a field that has been extensively investigated within the scope of power-plant control, aircraft, ships, command-and-control centers, intelligence operations, and information management systems. The SA process occurs, however, not only in the mentioned areas, but is the foundation for decision making in almost every field of endeavor. The elements of importance in gaining SA vary between different fields, but the general process of receiving information from the surroundings and filtering, connecting, prioritizing and extrapolating it to predict the future can be described by the same model.

Within the field of robotics, SA has been studied in a variety of applications. For example, SA research has been carried out on UAVs (Drury *et al.*, 2006a), poly-

[9]The technology for GPS navigation and the use of ultrasonic parking sensors, which have lately become standard in automotive industry, are examples of technology that has been refined within robotic research.

[10]For example navigation through waypoints predefined by a human operator.

[11]Endsley defines SA as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future". The formal definition breaks down into three levels:

Level 1 – Perception of the elements in the environment
Level 2 – Comprehension of the current situation
Level 3 – Projection of future status

The first level includes using senses such as visual, auditory and tactile to gain information about the surrounding environment. On the second level, the disjointed data from level 1 are synthesized, evaluated and prioritized in relation in order to the present goal to form an understanding of the current status. On the third level, the knowledge from prior levels is used to predict the oncoming future. A subsequent level demands the previous to be fulfilled. Thus, level 1 needs to be accomplished prior to level 2 and in the same way level 2 has to be reached prior to level 3.

morphic robots (Drury *et al.*, 2006b) and humans in cooperation with autonomous robots (Sellner *et al.*, 2006). One of the most investigated areas deals with scout robot operation in search-and-rescue and military settings (Yanco and Drury, 2004; Burke *et al.*, 2004; Casper, 2002; Casper *et al.*, 2004; Casper and Murphy, 2003; Drury *et al.*, 2003). The SA issues are closely coupled to interface design and in many cases the user interface design has been a driver for the evaluation of an operator's SA (Keskinpala and Adams, 2004; Nielsen and Goodrich, 2006; Fong, 2001). In robot research concerning SA, data collection is commonly carried out by established research methods such as user testing, interviews, questionnaires, subjective workload measures[12], observations, and communication analysis.

In the case of robot control, a fundamental part of attaining SA will consist of gaining knowledge of the surrounding environment's spatial layout, i.e. level 1 and 2 according to Endsley's definition. Previous SA research on robotics has shown that the way currently available user interfaces are designed – relying on real time video as the main feedback source – makes gaining SA severely more challenging compared to being on the spot in person[13]. But research comparing the performance of specific tasks with and without robots, for example, in terms of error rate and time consumption, has not been previously reported.

Portable User Interfaces

Ruggedness, compactness and portability are important features in mobile field applications. Unfortunately, the robotics industry has proved to be rather conservative regarding interface design. Most field robots are delivered with laptops or even bulkier operator control units (see fig. 2.9). This is the case although academic research has explored both the use of PDAs[14] and wearable computers for robot control (Fong *et al.*, 2001; SPAWAR, 2007a; Hüttenrauch and Norman, 2001; Hedström *et al.*, 2006; Rybski *et al.*, 2002). Also multi-modal and haptic interaction has been investigated (Skubic *et al.*, 2002; Perzanowski *et al.*, 2001; Ryu *et al.*, 2005) but little multi-modality has been implemented in commercial systems.

2.6 Approaches for User Involvement

Despite the similar aims of user studies carried out within robotics, approaches may have to vary significantly depending on the objective, resources and type of application. For example, evaluation with the elderly will differ vastly from tests targeting search-and-rescue personnel. Similarly, there is a great variation in the

[12] For example the NASA TLX method (Staveland, 1988)

[13] In the future, generations of user interfaces may include sensors superior to human ones (for example X-ray and olfactory [smell] sensors) and have a design so well suited to human cognition that tele-presence would be superior to on-the-spot experience; especially in high-risk applications including high mental stress and degradation due to protective gear.

[14] Personal Digital Assistant, i.e. handheld computers such as a PalmPilot or iPAQ (see fig. 3.18).

Figure 2.9. A typical field robot operator control unit (left), in this case the Allen-Vanguard Defender (right) recently acquired by the Swedish EOD units.

technical requisites in order to enable testing. The demands for reliability are, for example, completely different if testing in a museum compared to deployment on Mars. Hence, there is no obvious and uniform way to evaluate deployment. Established research methods may not fulfill the tele-presence[15], dynamics or autonomy of mobile robots (Scholtz *et al.*, 2004). Traditional methods, developed for other fields such as human-computer interaction, home electronics, social anthropology or psychology, need to be tested, merged and perhaps modified in order to facilitate the evaluation of robotics (Thomas and Macredie, 2002).

While the established high-risk applications to mostly concern only the surrounding physical environment, artifacts and substances, many of the applications under investigation include highly dynamic and responsive targets such as humans or other robots. Addressing the new applications will call for an expansion of the evaluation methods. Psychological, sociological, and ethical aspects will have to be taken into consideration when introducing robots as a tool for the targeting of counterparts. Some of these aspects have already been explored within the area of social and service robotics (Hüttenrauch, 2006), while others remain open for development (PerMIS, 2007).

Open Issues

In addition to addressing technical issues, which is to large extent the most common thing in robotics research, methods, tactics, and strategies for implementation need to be addressed. Approaches having as an overarching goal to include all factors

[15] When a person is enabled to feel as if they were present, to give the impression that they were present, or to have an effect, at a location other than their true location.

affecting development of military systems are emerging[16]. Robotics would benefit from a similar perspective.

The success within the area of commercial applications of tele-operation shows that reliable technical solutions are available. Similar benefits could perhaps be achieved in many other applications even today, provided they are properly approached. Implementation, i.e. how robots can be brought into everyday deployment under financial, legislative, ethical as well as users' and bystanders' interests, are issues open to be researched in parallel with technical development.

Previous user investigations have typically been in-depth studies of one particular group, but it is, in addition, of interest to carry out comparative surveys of several groups in order to explore their similarities and differences – an important issue since the costs of development and production of a multi-purpose robot could be shared between several user groups.

2.7 Lessons Learned and Challenges to be Overcome

The EOD applications show that robots hold the prospects to be of high value in solving dangerous tasks. In many arenas, however, progress is hindered by lack of knowledge about user requirements; something that has been clearly indicated by USAR fieldwork (Murphy, 2004) and by military end-users (Azzarelli, 2005). It could be argued that the robotics community in many cases has not taken into account what is proclaimed in every product development strategy – that the end-users should be involved early in the research and development process (Rubin, 1994; Gulliksen *et al.*, 2003; ISO13407-11, 2007). According to Gould and Siegwardt (Gould and Siegwart, 1985) a design process should follow three principles to achieve good usability:

1. Focusing early on users and tasks.
2. Employing empirical measurements.
3. Organizing for iterative design.

Part of fulfilling the first of these includes identifying who the user is (Kujala and Kauppinen, 2004), something that is not as much of a problem for high-risk applications as it may be for research in general. The next step, on the other hand, incorporating the users in studies, poses a problem, since many high-risk user communities are closed for reasons of safety and security. Another aggravating factor is

[16]"Military technology is the science which describes and explains how technology influences military activity at all levels and how the profession of an officer affects and is affected by technology. Military technology is based on several different subject areas from different disciplines and combines understanding of the military profession deriving from social science with the foundations of natural science and with a superstructure and dynamics supplied by engineering. Military technology deals with matters which ultimately have to do with an officer's ability to carry out his profession. It is important in this connection to remember that technology *per se* cannot solve any military problem." (Tornerhielm, 2007, p. 9)

that as robotic features possess entirely novel features making the matter of taking end-users opinions into account a task beyond just carrying out an inquiry. Without having any hands-on experience, users will be unable to provide a valid opinion. Only after having attempted to solve likely tasks under reasonably realistic circumstances will they be able to define their requirements and be a valid participant of iterative design.

Chapter 3

Methodology

This chapter presents the methodology, settings and outline of the five user investigations comprised in this thesis. The chronological order of the different user investigations, as well as other phases performed, is illustrated in figure 3.1. After commencing to survey the research field, an attempt was made to initialize cooperation with MOUT troops. These initial attempts were rather exploratory, since the involved parties (academic researchers, military units, and procurement personnel, see 1.3) had not cooperated before and were inexperienced in user testing. Although the initial attempts did not facilitate the level of realism aspired to, they did point out how proceed. The next phase, the main trials, included redirecting the project towards robotic hardware more suited for realistic testing with the military. The main trials included two phases referred to as the pre- and main studies. The long-term robot trials with the secondary user group, the SWAT police, were

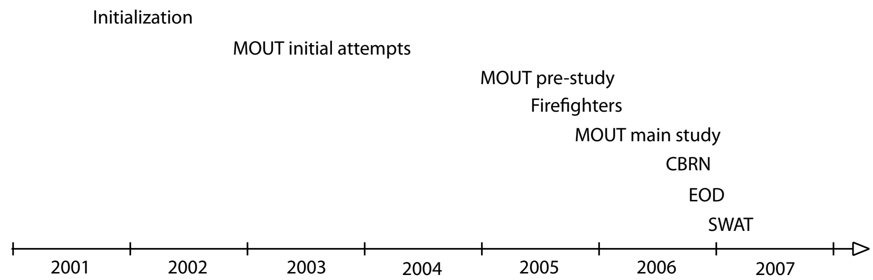

Figure 3.1. The chronological order of the various phases included in this thesis.

the last of the user investigations to be performed. The results from the studies of the primary and secondary user groups are to be found in Chapters 4 and 5 respectively.

In parallel with the main trials the three reference groups were surveyed (firefighters, CBRN teams, and EOD teams). These groups were taken in consideration in order to provide a reference to which the results from the primary and secondary user groups could be compared and discussed. In addition, this phase contributed to a deeper understanding of field robot deployment. The investigation of the reference groups included into account both taking knowledge from users with experience from robots as well as investigating the feasibility with users who had not worked with robots before. The main issues investigated concerned: what are the main characteristics of the different groups and what are their primary tasks? What factors constrain them the most? How do they currently deploy robots or how could they benefit from robots in the future? I.e. the investigations of the reference groups had a similar aim as for the primary and secondary user groups but were surveyed in significantly less depth.

After having compiled the findings of the five user groups they were compared according to 20 criteria. The overall goal of the comparison was to see how alike the different groups are and the extent to which it would be possible for them to deploy the same robot and methods. The results of the references groups and the comparison are presented in Chapter 6.

Before going into detail on how the different users were investigated, a general description of the data collection methods is given according to which the five groups were investigated. The description of the data collection methods is kept general and given in advance as many of them were deployed on several user groups. Reasons for the selected methods are given in the discussion Chapter 6.

3.1 Methods of Data Collection

Documentation Studies

When available, reading manuals and instruction videos was a good way to get to know the basics of the users' working procedures, learning their terminology, etc. Although for many vocations, documentation mainly covers the basics while high-level skills are passed on during training and real missions.

Interviews

Interviews are a central method of data collection when it comes to gaining a holistic view of a user group(Silverman, 2006, p. 109). An advantage compared to many other methods is that interviews enable verification of both content and validity by follow-up questions. Interviews also permit the possibility to go in-depth or expand the investigation into previously undiscovered areas. When used to investigate robot deployment, interviews can be regarded as indirect data collection, as they investigate the users' conception of events, which may differ from what actually occurred. The interviews carried out during this project can be categorized into three groups:

1. Pre-deployment interviews – This category of interviews was conducted at the beginning of a user study with the purpose of gaining knowledge of their

current strategies and limitations. Another reason for the pre-deployment interviews was to survey in what way robots may be appropriate. These interviews were carried out with respondents that had extensive experience of the field being investigated. They were conducted off-scene, for example in a conference room, and often included a demonstration of the users' gear. Although a number of predefined topics were to be addressed, the interviews were open to extension and modification. The pre-deployment interviews were recorded and transcribed.

2. Field interviews – These interviews were carried out spontaneously whenever appropriate in the field and held in an informal manner. They aimed to further examine the established procedures as well as the ideas and experiences of working with the robot. Audio and video recording was attempted but was often unsatisfactory in the noisy environments. Writing down notes whenever possible proved to be the most appropriate means of documentation.

3. Post-trial interviews – These interviews were carried out after the trials with the purpose of documenting and evaluating past robot deployment. Just like the pre-deployment interviews, these were carried out off-scene but in this case with one respondent at a time. Again audio was recorded and transcribed. For groups having prior experience of robots, the issues within this category (experiences from robot deployment) were investigated at the same point in time as those within the pre-deployment interviews. In these cases, the interviews were carried out with the respondents in groups.

Observations

The performed observations (Silverman, 2006, p. 78) had two purposes. First, to gain knowledge and understanding of the users in their operational environment, second, to evaluate robots in realistic settings. The two processes were carried out in parallel although the former was initiated at an earlier stage. As opposed to interviews, observations constituted a direct method of data collection.

High-risk workers are in general accustomed to having both instructors and visitors amongst them during training. Within the military, armlets are used to distinguish observers from participants, which made it possible to have full access for observation during maneuvers (see fig. 3.2). For safety reasons hearing- and eye protectors had to be worn when using blank ammunition indoors.

Participatory approaches were used when the trained operators were not available. This was possible since the author is an army officer and was trained to operate the robot. During the participatory tests the researcher took the place of the operating soldier in conformity with regular rules and demands.

Figure 3.2. Armlets are used to distinguish observers from participants. The officer appearing closest in the picture wears a blue and yellow armlet which indicates that he is an instructor; he deliberately positions himself completely visible to the enemy while the others are in shelter.

Questionnaires

A questionnaire was conducted as a mean of investigating previous findings across a wider number of respondents at the end of a long-term trial (Trost, 2001). The higher numbers of respondents enabled quantifiable performance metrics as a valuable complement to the qualitative findings rendered by the other data collection methods.

Exploratory Testing

Exploratory tests (Rubin, 1994, p. 31) were conducted to identify how to use the robot and to find new ways of solving tasks. The tests were performed by having the robot crews carry out iterative trials on the same task to find a suitable methodology. For groups without experience of robots, the exploratory testing was carried out in parallel with learning to operate the robot.

Validation Testing

Validation tests were carried out to verify usability during technical development. The early state of development did not call for deploying quantitative methods[1].

[1]Such as when carried out under video documentation in usability labs to evaluate different design alternatives.

Informal semi-structured testing accompanied by open discussion and approaches such as *think-aloud* (Rubin, 1994, p. 21) and *walk-through* (Rubin, 1994, p. 217) were considered sufficient to provide guidelines for prototype development at this stage.

Real Deployment

Deployment in real missions is of course the most genuine of all tests and some of the investigated users were able to provide knowledge from such. Data were gathered indirectly by post-deployment interviews, but also to some extent by direct observation of training sessions which the users designed carefully to simulate reality.

Post Verification

All results within this thesis have been verified with representatives of the investigated user groups. Verification was carried out at the end of the analysis process with the results compiled as field report.

Experiments

A particular set of quantitative findings within the military study (that using the robot will take longer and be more liable to error than traditional methods) was replicated in an experimental setting in order to enable quantitative investigation (to gain statistically verified data concerning the previously identified phenomena, see 3.3 and appendix A) . In addition, an attempt was made to carry out comparative tests for solving tasks with and without robot aid within the framework of the military training maneuvers. It was found that the users had not reached a high enough level of training with the robot system to permit fair comparison. It also proved inappropriate to carry out these kinds of validations in large-scale military operations since the surrounding circumstances could not be kept constant (Rubin, 1994, p. 28).

3.2 MOUT – Initial Attempts

The first attempts at user collaboration conducted within this project included bringing together researchers of autonomous robots and officers specialized in urban warfare. The purpose of the initial attempts was to include end-users early in the design of autonomous robots. The trials were carried out in two of the facilities regularly used for MOUT training [2].

[2] Stora Sätra, Kungsängen and Skogaholmsbageriet, Kungsholmen, Stockholm.

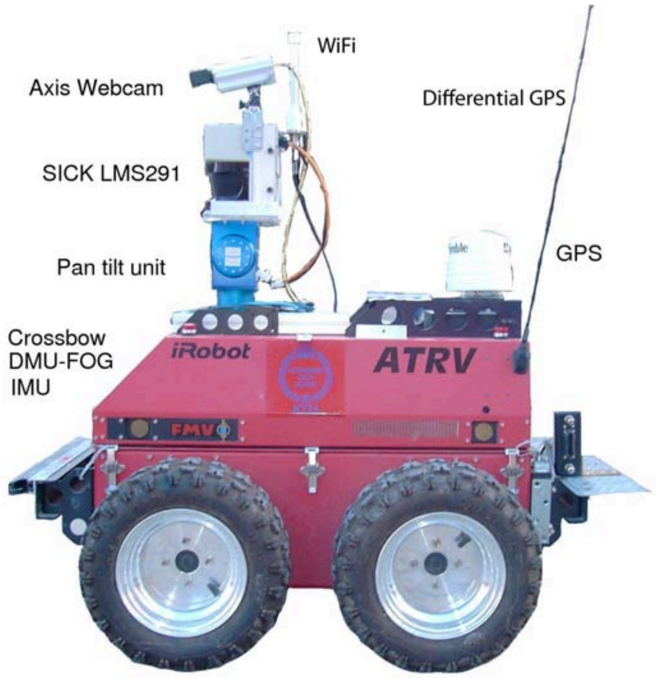

Figure 3.3. The ATRV robot equipped with an SICK LMS 291 laser scanner, a set of 12 sonar range sensors, an Axis Network Camera, a Crossbow DMU-FOG inertial measurement unit and a Trimble differential GPS. The laser scanner and the camera were mounted on a pan tilt device.

The ATRV Robot

The robot platform developed for the initial trials, an iRobot ATRV (All Terrain Robot Vehicle), had both tele-operation and autonomous capabilities such as *Follow-Me, Road Follow, Explore,* and *Go-To* (Folkesson, 2005) (see fig. 3.3, 3.4, and 3.5) .

The *Follow-Me* and *Road Follow* functions are intended for logistics in a military context. Convoy vehicles have no, or significantly less, armor than combat vehicles and are therefore vulnerable targets. During operation on foot, the physical workload imposed on soldiers by just transporting their gear is a major issue and a robotic "mule" is a tactical application of interest.

Explore and *Go-To* functions are needed because the unit having best spatial knowledge will be superior even if inferior in other respects. For example a Marine Corps war fighting experiment on battalion level showed the hit-rate for stationary vehicles to be 71% while only 29% for vehicles on the move (Catto, 2001). I.e. increased knowledge of the surroundings and preventing stoppages due to unforeseen obstacles can drastically cut risks in urban warfare.

Figure 3.4. The Compaq iPAQ PDA displaying the tele-operation screen for line-of-sight tele-operation of the ATRV robot.

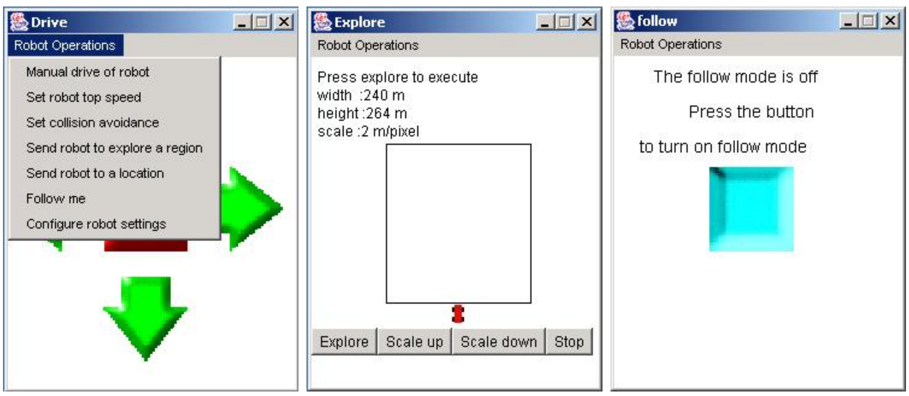

Figure 3.5. The PDA interface was designed with a separate window for each mode (*Follow-Me, Explore, Go-To,* and *tele-operation*).

Tests

After having implemented the autonomous behaviors on the ATRV and having them technically validated, the researchers were eager to have the end-users' views of the system. Officers from the LG (see 1.5) tactical development group represented the primary user group but also members of the Army Combat School[3], FMV UGV procurement personnel, and officers at the Advanced Command Program[4] participated in the tests. But, as it turned out, the robot did not prove to form a feasible basis for mutual exchange. The step between the available autonomous functionalities and a final product was just too large to serve as a starting point for reasoning around tactical benefits (see fig. 3.6).

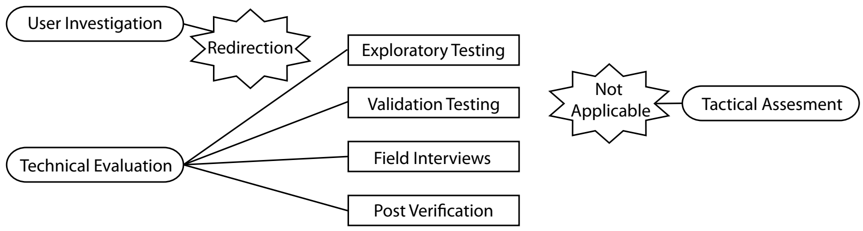

Figure 3.6. Illustration of how the applied data collection methods contributed to the Initial Attempts.

Although the users agreed that UGVs have potential, the substantial lack of realism left it unclear how the capabilities of the ATRV would fit into the military tactics. One of the users' main conclusions was that technology was not yet ready and will not require any serious consideration from their side for a long time. Instead of uniting the two parties, the attempt showed that while researchers have a tendency to see possibilities, high-risk workers focus on any flaws that may endanger reliable operation (see fig. 3.7).

Having come not so very far in terms of involving the user it was decided to take a step back in terms of the technical complexity. In the interest of robustness, reliability, and usability, it was decided to replace the ATRV with a purely teleoperated and more field-adapted robot. It was also decided to carry out an in-depth user investigation and to investigate the feasibility of the platform to be tested prior to attempting any further user trials.

3.3 MOUT – Main Trials

The aim of the main trials was to gain a comprehensive view of the deployment of man-portable robots within MOUT. This included: investigation of the users' characteristics, task analysis (Kirwan and Ainsworth, 1992), and identification of

[3]Swedish: Markstridskolan

[4]I.e. the Lt Colonel course at the National Defence College, Swedish: Chefsprogrammet

Figure 3.7. From left to right: the researchers, the robot and the end-users. The autonomous robot was not sufficiently developed to serve as a starting point for end-user testing.

limiting factors of today's activities. The main trials also had the objective to embed a robot system with the chosen user organization in order to assess present technology in a realistic setting. This included: identification of suitable robot missions, implementation of a robot, investigation of pros and cons, and evaluation of technical feasibility.

Outline

A pre-study initiated the main trials with the purpose of investigating the user and exploring the ways in which they could benefit from using robots. This included implementing and performing exploratory testing of the robot during four military training maneuvers from January to March 2005[5].

Most of the testing within the pre-study was performed with the reconnaissance squad (see fig. 3.8). On the final maneuver the author operated the robot in order to enable deployment at company level. Pre-study data were gathered through military manuals, field observation, formal and informal interviews, and participatory observation (see fig. 3.9).

The pre-study led to a decision to perform long-term testing on a larger scale during the following year. A selection of standard procedures was redesigned to include the robot. Once mastered by the operators, the new procedures were demonstrated to the rest of the company. It was then up to the commanders of the company to deploy the UGV as they considered appropriate during their training.

[5]Fagersta 1-3 February, Hallsberg 8 February, Jordberga 26-27 February, Skövde 14-16 March, 2005

Figure 3.8. The reconnaissance squad which performed most of the tests within the pre-study.

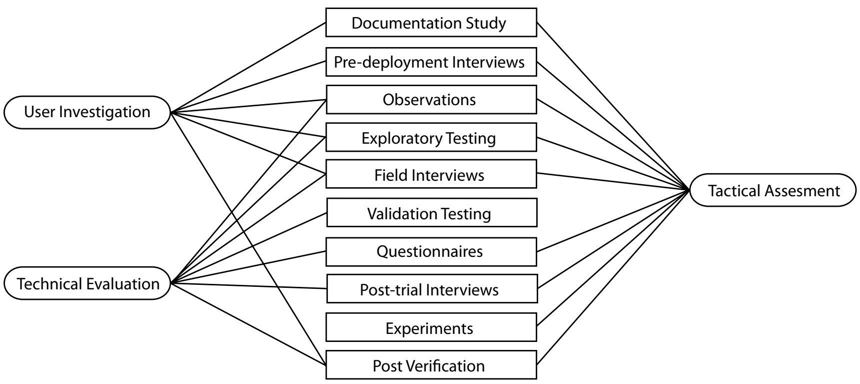

Figure 3.9. The various data collection methods and how they contributed to the main trials.

Figure 3.10. The MOUT company serving as test group for the Packbot trials.

During the six-month test period of the main study, the company acted as a cohesive unit on five training maneuvers which included from 200 to 6000 soldiers and lasted for three to six days[6]. The maneuvers were set up with an initial phase of political conflict, mobilization, and handover of tactical responsibility to the company. The robot had no role during these initial phases which, generally speaking, lasted for one-half to one day. The robot, however, entered the scene during combat for a total of 16 days. Again the author acted as robot operator during one maneuver when the soldiers trained to operate the UGV were not available.

User Group

The Swedish Armed Forces are based on the conscription of 18- to 24-year-old males. The army uses conscript soldiers in positions up to second platoon commander. Higher positions are held by professional officers. Women can volunteer to do military service, and all positions within the Swedish Armed Forces are open to both sexes. The conscription service ranges from eight to fifteen months. Standard units such as the company under study are trained in one-year cycles.

The appointed test unit, the 6th Urban Warfare Company of the Royal Life Guards, Kungsängen, Stockholm (see fig. 3.10), consisted of 200 soldiers, 7 professional officers, 16 Armored Personal Carriers[7] (APCs), and 10 logistic vehicles. Ten additional officers served as instructors, about three percent of the company members being female. Military training initially targets individual behaviors; the complexity of training is gradually increased at squad-, platoon-, company- and, finally battalion level. Lower-level training receives more training since higher-level training requires larger logistical, personnel, and organizational resources.

The company under study is a highly specialized unit which directs about 90% of its training towards urban intervention. Ordinary infantry troops have a different

[6] The maneuvers took place in: Fagersta 1-4 November 2005, Enköping 8-9 November 2005 (Demo 05), Marma 5-9 December 2005, Fagersta 6-9 February 2006, Jordberga 5-7 March 2006, Norrköping/Stockholm 20-26 March 2006.

[7] Tracked vehicles, armed with 20 mm cannons, capacity to carry 11 people (Hägglunds Vehicle AB, PBV302).

set of strategies and are primarily directed towards operation in non-urban terrain (open terrain or forest). Many current conflicts, however, take place in urban environments, and a corresponding redirection of armed force training is on-going.

Test Facilities

MOUT units require access to urban surroundings suitable for training. This includes moving entire units nationwide, or even to neighboring countries (e.g. Poland and Germany), in order to access appropriate exercise areas. All tests were carried out in facilities regularly used for military training. Deserted and partly demolished industrial and residential buildings offered an environment similar to those expected during combat operations (see figs. 3.11 and 3.12). The test period spanned from autumn to spring and temperatures from -15° C to +15° C. The test environment was not adjusted in any way.

The Robot System

The Packbot Scout

The iRobot Packbot Scout is a man-portable robot (700 x 500 x 180 mm, 18 kg) tele-operated by using video feedback (see fig. 3.11 and 3.13). The track propulsion system includes articulated tracked arms (flippers) which can be rotated 360 degrees. The top speed of the robot is 3.7 m/s and the NiCd batteries allow an operating time of about three hours. The Packbot is equipped with a fish-eye daylight video camera, IR-camera[8], an IR-illuminator, a GPS receiver, an electronic compass, and absolute orientation sensors (measuring roll and pitch). Communication between the robot and the user interface is achieved through WiFi radio[9].

The Payloads

A number of payloads were added to the Packbot during the main trials. The same Direct Fire Weapon Effects Simulator that is used for combat training was mounted on the robot (DFWES-Saab BT46). The system consists of a laser mounted on the firearms and a sensor vest worn by the soldiers. The laser beam simulates the bullet during training with blank ammunition. Adding the fire simulation system enabled the soldiers to engage the robot with their firearms during training (see fig. 3.13).

Two more payloads were developed for the military trials, a flashlight for illumination in dark premises and a Claymore mine (inert), both triggered by remote control (see fig. 3.14). A siren on the robot simulated detonation of the Claymore mine. The choice of weapon was not a result of detailed consideration. A Claymore mine, which is a standard weapon for infantry troops, would most certainly destroy the robot if detonated. The mine may also be a much too powerful weapon for

[8] In the close to visible infra-red spectrum.
[9] IEEE 802.11b (2.4 GHz)

Figure 3.11. One of the deserted steel factory buildings in Fagersta, Dalarna. To *seize* such a building is a typical task for a company.

Figure 3.12. The sugar refinery used for training in Jordberga, Skåne.

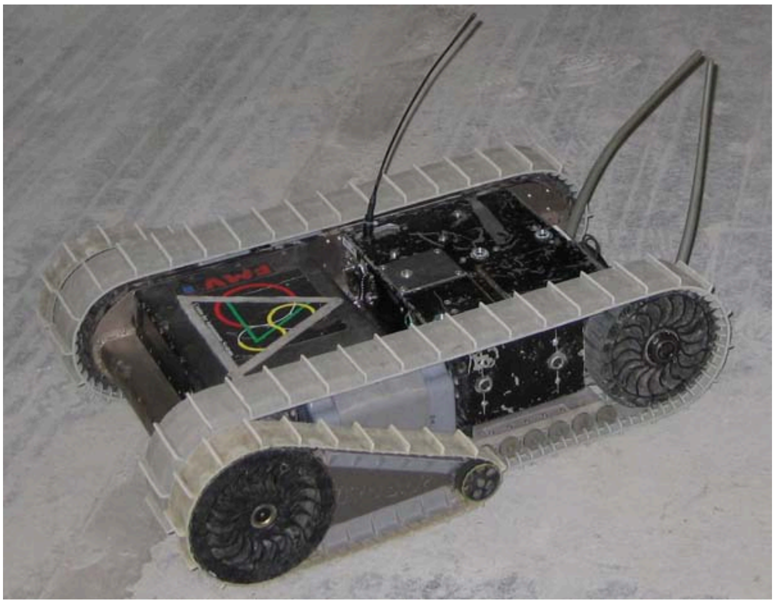

Figure 3.13. The Packbot Scout with the DFWES system enabling the soldiers to engage the robot in the same way they engage each other with firearms during training. The robot had two DFWES sensors (black circular) on each side, three on top, and two in the rear.

indoor use or while in the vicinity of one's own personnel. It does not, however, have to be aimed very accurately. Non-lethal weapons such as flash-bang grenades may be a more suitable option for initial implementation.

The Laptop Operator Control Unit

The standard operator control unit (OCU) delivered by iRobot consists of an Amrel Rocky Patriot rugged laptop (312 x 246 x 65 mm, 6.5 kg), fitted with a three degrees of freedom (DOF) joystick[10], and a keypad for controlling IR-lights, brakes, the video frame-rate and toggle display-alternatives. Apart from showing the video stream (only one of the two cameras can be used at a time, 10-15 frames per second) the OCU indicates battery power, motor temperature, compass reading, GPS position, and roll/pitch. (see figs. 3.15, 3.16 and 3.17). The laptop OCU was the primary user interface during the main study within the main trials.

[10]Sideways, forward/backward, and twisting the knob (to control the flippers).

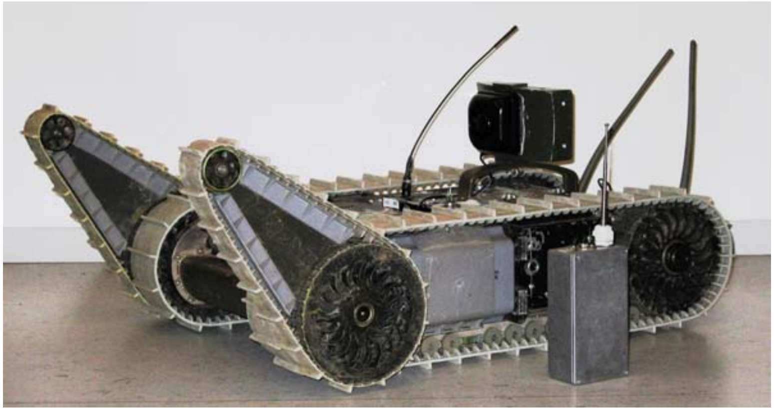

Figure 3.14. The Packbot Scout equipped with the Claymore mine (on top) and the DFWES system. Added payloads were controlled by a separate radio control, to the lower right the remote control for payload operation.

Figure 3.15. The iRobot OCU based on a rugged laptop and a joystick.

Figure 3.16. The graphical user interface (GUI) of the iRobot OCU.

Figure 3.17. The joystick and control buttons of the iRobot OCU.

The Handheld Operator Control Unit

In order to explore the feasibility of smaller OCUs, software was developed for operation with a PDA. The chosen platform, an iPAQ h5550 (see fig. 3.18), runs Linux, has an integrated WiFi radio link, and a 320x240 pixel TFT color touch screen. The graphical user interface (GUI) developed for the iPAQ shows the video from one of the two cameras, receives the operator's drive commands, and permits toggling functions on/off.

The driving commands are entered either by pressing the arrows overlaid on the video screen or by using the hardware buttons at the bottom of the PDA. The four green triangles indicate forward/backward, left/right, and the centered red square indicates stop. The drive commands are given impulse-wise in the sense that one push on the forward button means go slowly forward. Another push means go a little bit faster, another push further faster still and so on. The robot can be brought to a halt either by pushing the backwards button as many times as the forward or backwards button had been pressed, or, by pushing stop; the left/right control works the same way. A feature that proved useful was that pushing the forward button while turning will stop rotation without stopping the forward/backwards motion (i.e. letting the robot continue straight ahead/backwards).

Just as the drive commands, the flippers were controlled through the symbols overlaid on the video, the blue triangles in the right upper and lower corner. The flipper positions are illustrated graphically to the right in the command window. Three other frequently used commands were also overlaid with buttons on the touch screen, the video on/off, the brakes on/off and the IR-illuminator on/off. The video on/off switch was placed with easy access since showing the video took up a large part of the iPAQs' processor's capacity and thereby delayed other functions such as the drop-down menus (to access other controls than those overlaid on the video). Hence, if aiming to navigate in the menus, the video stream could first be turned off to decrease latency (the drop down anyway blocked the video).

Status information and warnings, such as low radio connection or low battery power, are displayed with text messages in the command window below the video screen. The data from the GPS, compass and absolute orientation sensors were displayed numerically in a window replacing the video window. The handheld OCU was primarily deployed during the pre-study (about half the time).

The Wearable Operator Control Unit

A prototype wearable OCU was developed in order to investigate the feasibility of future soldier command-and-control systems for robot control (Hedström *et al.*, 2006). The prototype system was based on a 650 MHz ULV Celeron computer with a Compact Flash memory card for a hard disk, a Micro Optics SV-6 "eye-monitor"[11], and a Logitech WingMan Cordless Gamepad. The entire system was integrated into an army combat vest (see fig. 3.19).

[11] 640*480 pixel resolution

Figure 3.18. The PDA running the GUI developed for Packbot control.

The GUI was designed with only two screens, one streaming the video and one explaining the functions of the gamepad. The speed, turn rate, compass course, and status information could be set to be overlaid on the video (see fig. 3.20). Control was carried out with joysticks and buttons on the gamepad according to existing computer gaming standards (left joystick for forward/backwards, left/right and the right for control of flippers). The wearable OCU was subjected to validation testing during the main study but was not used during the tactical tests due to limitations of ruggedness and because the eye-monitor did not fit with the military helmets and goggles.

Accessories

A carrying system was added to both the robot and the laptop OCU to enable hands-free portability (see fig. 3.21). Other field adaptations included fitting the joystick, keypad and cable connectors with protective covers. A small whiteboard was attached to the laptop with Velcro so that it could be easily removed and used by the operator to sketch the explored region.

During the course of the test, the system also incorporated extra batteries, chargers, basic spare parts and rope for lowering the robot into premises, a carrying system, and protective cases for all components. Extension cords and external

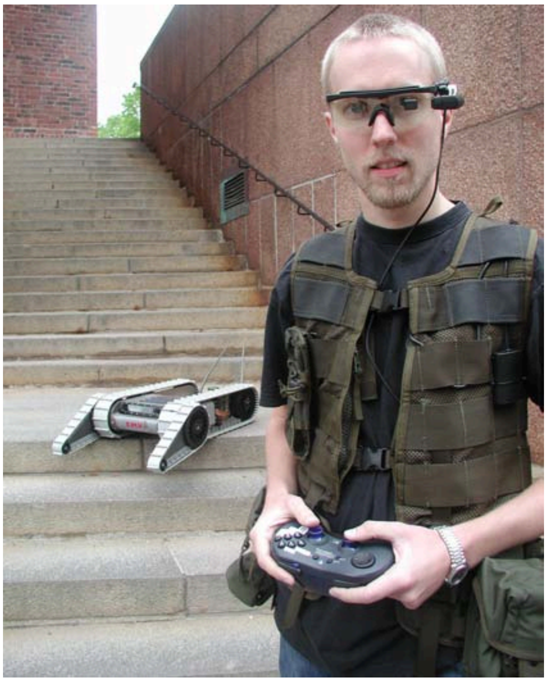

Figure 3.19. The wearable OCU developed for the trials.

antennae with magnetic stands were provided for operation from within armored vehicles. A telescopic rod, which could be attached vertically to the robot to detonate trip-wired explosives, was also included.

Command-and-Control Interface

A data transmission interface was developed in order to demonstrate integration of UGV as a sensor in network-centric warfare. The unit included a laptop which received the video and GPS data passively from the Packbot and fed it into the army's prototype command-and-control. The video was reformatted to S-video and the position data were formatted according to the NATO standard Stanag 4586 (NATO, 2007) and transferred via TCP/IP. The system enabled video and GPS data from the Packbot to be displayed at any node in the command-and-control system[12].

[12] This was demonstrated at Demo 05 in Enköping 8-9 Nov. 2005.

Figure 3.20. The main window of the wearable OCU showing the video with status data, speed, and turn rate overlaid.

Robot Implementation

During the pre-study, the robot had only been in the hands of the MOUT company during the individual trials. For the main study, except during modifications and repairs, the robot was kept by the company. All transport, maintenance and charging of the robot system was carried out with the test groups' ordinary resources in order to expose the system to realistic stress. The users were instructed to treat the robot as a standard piece of equipment and they were told that damage and wear was considered an expected side-effect of the study. The robot's robustness was stated to be comparable to the users' radios or optical equipment.

In agreement with the commander of the Royal Life Guards, one officer and two soldiers were trained to operate the robot during the main study. Unfortunately, one of the soldiers was released from duty due to medical reasons after two months. Operating the Packbot was performed according to the regular rules and demands of the unit.

No military tactical concepts of robot deployment existed when the robot was introduced to the MOUT company, nor did the users have any well-defined opinions about how the system could be implemented. This was the first acquaintance with robotics for most of them. The delegated operators had no previous experience with robotics, but were accustomed computer users and had some experience with

Figure 3.21. The iRobot OCU fitted with a carrying system allowing hands free portability.

RC-craft[13].

Three levels of operator training were defined: 1 – *Basic Level*, 2 – *Map and Search Level*, and 3 – *Tactical Level*. Training for the *Basic Level* followed the scheme developed during the pre-study. This included briefing about the robot, basic driving, and familiarization with the appearance through video feedback. After the basic training, which took one day, the operators were able to perform simple missions and continue to practice on their own. Since the higher level behaviors had not yet been defined, the higher level training was to a wide extent performed concurrently with exploratory testing. The *Map and Search Level* incorporated the ability to sketch explored premises and to search for persons or Improvised Explosive Devices (IEDs).

After having acquired personal skills in robot control, the operators were trained to execute missions in conjunction with others, i.e. the *Tactical Level*. Initially this was carried out in pairs, where the operator and an assisting soldier were trained to act as a team (see fig. 3.22). After approximately seven days of practice[14], the pair was integrated at group, squad and platoon level, and performed their tasks synchronized with other mission activities (see fig. 3.23). While the two first

[13]Remote controlled planes, cars or boats

[14]The basic EOD robot operator course at SWEDEC is five days.

Figure 3.22. From left to right: the Packbot Scout, the robot assistant, and the robot operator. The robot is about to move up the staircase to the left; meanwhile, the assistant is ready to act in the most hazardous direction, in this case considered to be the staircase. The operator controls the robot from a previously secured area. Observing the robot in line-of-sight provides better situational awareness than having to rely on the user interface. The assistant, therefore, supports the operator with voice commands as long as he has the robot in sight.

training levels only included the operator and the assistant, the third level also required adaptation of the group in which the robot operated.

Once the operators had acquired the necessary skills, demonstrations were carried out for one platoon at a time and included a briefing about the system, safety issues, and a demonstration of an exploration mission. It was emphasized that the use of the robot was a test and that some aspects could not be expected to reach full effectiveness until after some time of tactical development and training. After the demonstration the MOUT company was free to use the robot system as they pleased. During the training maneuvers, either the DFWES-system (see 3.3) or the training officers could determine that the robot had been neutralized; if so, the robot was returned to the transportation vehicle from where the operator could retrieve it as a new robot. There was no set limit for how many times this could be repeated, i.e. the company had a fictitiously unlimited resource of robots. The company had access to one robot system on all maneuvers except for the 2006 final maneuver when two systems were deployed in parallel.

Prior to testing with conscripts, military safety regulations required the system to be reviewed by the Armed Forces Safety Board, which identified the risk of

Figure 3.23. From the left: the platoon leader, the robot operator, the group leader and then the private soldiers. The platoon leader is using the robot system to carry out exploration around the corner. The group leader is observing the neighborhood and the soldiers are ready to act in hazardous directions.

the robot falling onto a person situated below as the largest hazard during tests (Military Headquarters Safety Board (Swe), 2004). All participating personnel were informed about robot safety prior to every training maneuver.

Data Collection and Analysis

Military training manuals and videos proved valuable tools to get familiarized with the users' circumstances, their terminology and their work schemes (see fig. 3.9). In addition, participating in one national[15] and one international workshop[16] on urban warfare presented the opportunity to investigate areas of tactical development.

Observation, with video and photography documentation, was an essential research method for the project. All three types of interviews previously described (see 3.1) were conducted during the main trials. First, two officers were interviewed before the long-term test regarding what applications they thought might be feasible for robot implementation. The results were verified by the respondents after transcription. Second, participants were interviewed about their established procedures and their experience working with the robot. These interviews were carried

[15]The annual MOUT development workshop of the Army Combat School, Borensberg 10 May 2005.

[16]Trilateral workshop on Urban Warfare, The Ministries of Defence of Germany (FhG-INT), The Netherlands Defence Research Institutes (TNO), Swedish Defence Research Agency (FOI) and Swedish Defence Materiel Administration (FMV), 18-19 May 2005, Stockholm.

out spontaneously at appropriate times in the field, and were held in an informal manner. In some cases these interviews were documented with video or notes, but mostly the data was written down at a later time. Finally, after the main study, four soldiers and six officers were chosen for in-depth interviews regarding their experiences when using the robot. An anthropologist who had not participated in the field studies was recruited to perform final interviews. These interviews, which lasted anywhere from 30 minutes to one hour each, were recorded and transcribed[17]. The semi-structured interviews provided the opportunity to extend and modify the questions for in-depth investigations.

At the end of the main trials the 41 most experienced participants (36 soldiers and 5 officers) were selected for the questionnaire study. The topics explored in the questionnaire were aligned with the topics of the post-trial interviews. The questionnaire contained 14 main questions which were either statements to be rated on a five-point scale, or open-ended questions (the questions are included as footnotes in Chapter 4). The respondents were given the option to add alternatives they believed to be missing. Participants took from 20 to 60 minutes to complete the questionnaire. The post-evaluation (interviews and questionnaire) was designed to document the missions that had been performed, to explore opinions about the robot's efficiency/functionality, its significance compared to other equipment, to probe ideas for future development and ethical considerations, and to investigate whether acquisition was recommended by the end-users.

The Mapping Experiment

The object of the experiment was to investigate and measure how well an operator gains spatial situational awareness while using a video-feedback robot compared with being personally present. This was carried out by having two groups of ten civilian test persons carry out a mapping task, one group with and the other without the robot[18]. The two groups were compared as to time taken, error rate, and accuracy. Attaining a controllable experimental setting required a number of abstractions such as simplifying the environment, eliminating distractions and disregarding benefits that might come with experience (see fig. 3.24). A detailed description of the experimental setting is given in Appendix A.

3.4 SWAT police

The SWAT study was initiated to compare the results gained during training to those of a user subjected to genuine risk (the investigated SWAT unit performs real missions on a daily basis while the MOUT did not perform any real missions during the test period). The study also broadened the scope of knowledge regarding the feasibility of robots within another high-risk work group and provided an

[17] Each interview took eight hours on average to transcribe and about as long to analyze.
[18] Stockholm February 2006

Figure 3.24. The mapping experiment was carried out in a basement and included two groups of ten test persons. One group explored the map through tele-operation and the other did the mapping by walking through the premises themselves.

opportunity to carry out continued user-governed assessment of the Packbot Scout in realistic settings (see fig. 3.25).

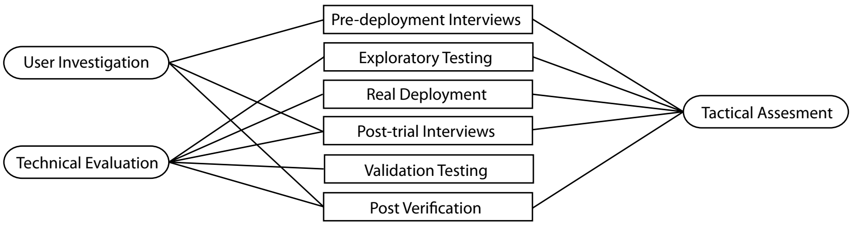

Figure 3.25. The various data collection methods and how they contributed to the study of SWAT units.

Implementation of the Packbot (see 3.3) together with the laptop OCU (see 3.3) was initiated in mid-December 2006[19] when researchers met with representatives from the unit's development and training team. The meeting included working out guidelines and liability issues for the trials. It was decided to carry out the testing

[19] 14 December 2006

with one of the eight SWAT teams until May 2007. The initial meeting, moreover presented an opportunity for pre-deployment interviews.

The appointed team was taught the basics for robot operation a few days later[20] and then it was up to them to use the robot as they considered appropriate during training and real missions. The one-day training session included a brief description of how the military had been using the system in urban intervention during previous trials. Two team members were appointed to act as robot operators during the trials. It was declared that deployment in real missions was of great interest to the study and that it did not matter if the robot was damaged. The police chose to rely on the safety review of the Military Headquarters Safety Board (see 3.3) and permitted testing both during training and real missions. An agreement between the police and KTH (the official owner of the Packbot) exonerated the police from any liability for damages or wear to the robot; KTH in turn was released from any responsibility of damage inflicted during the robot tests.

After handover, the two operators continued to train with the robot, on average once a week. They also gave the other team members the opportunity to familiarize themselves with the robot's performance and to try operating it. Training was carried out both outdoors and indoors and included passing obstacles, as well as operation in different lighting conditions. The task practiced the most was mapping previously unknown premises and locating suspects. During three training sessions the operators first explored premises and then executed a strike mission into the investigated area to evaluate the benefit of previous knowledge.

Three months into the trial[21] the robot was equipped with a distraction siren (see fig. 3.26). The siren was originally an alarm siren for intruder deterrence, developed and manufactured in Stockholm by Inferno[22]. The patented siren generates a high-pitch noise which is extremely unpleasant to the naked ear. Four different frequencies are modulated to cognitively overload the auditory organ while not causing hearing impairment (123-127 db(A)). Wearing hearing protection or plugging one's ears blocks the effect. The distraction-siren payload was evaluated in a trial mimicking a hostage situation during which one police officer was acting as a hostage taker and one police officer was acting as hostage; both previously unacquainted with the distraction-siren. The researchers had regular contacts with the unit to monitor the advance and to provide technical support. The interviews with the two operators were carried out in early May 2007[23].

3.5 Firefighting

The investigation of robot deployment within the fire brigade was carried out during a one-day visit[24] to the fire station in Södertälje. Two senior firefighters hosted the

[20] 19 December 2006
[21] 18 March 2007
[22] www.inferno.se
[23] 8 May 2007
[24] 5 May 2005

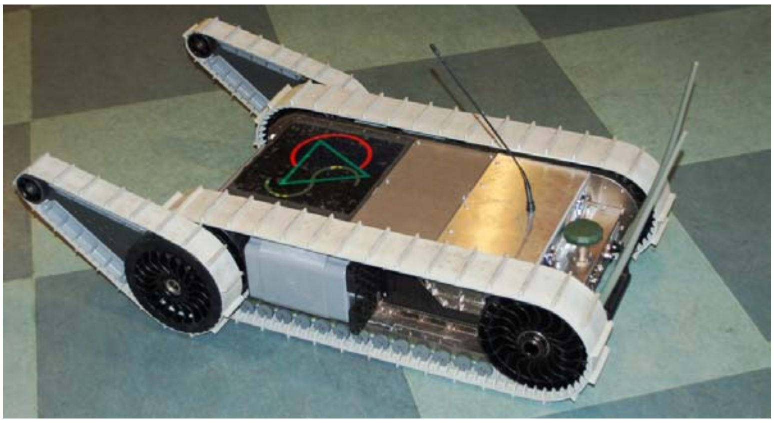

Figure 3.26. The Packbot Scout with the distraction siren (centered on top of the robot).

visit, which was initiated with a one-hour interview followed by a demonstration of the firefighting equipment in general and a more specific demonstration and discussion of the robot which is used to handle gas cylinders (see fig. 3.27). The initial interview was held in an informal manner with both respondents at the same time. The interview session included watching videos of the real neutralization of acetylene cylinders.

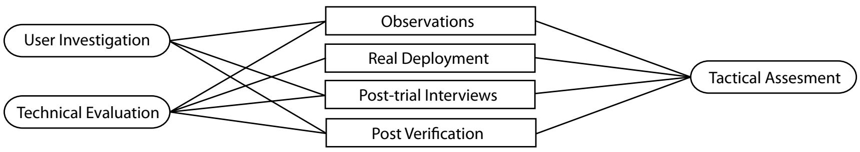

Figure 3.27. The various data collection methods and how they contributed to the study of firefighters.

The robot deployed by the firefighters is a modified rock-drilling machine which was first used by the police and later donated to the fire brigade (see fig. 3.28). This is the only robot of its kind and no application-specific documentation, manuals or training courses exist; the firefighters operating the robot are the only ones familiar with the system. Overhauls are carried out by a local workshop. There is no provider of technical support for the control system and the video feedback, which are both wireless. The robot is powered by a gasoline engine and actuation is hydraulic. The arm has a single DOF shoulder joint, a telescopic boom, a two-DOF wrist and a gripping claw. The system is 1 m wide, 1.8 m long, 0.7 m high, weighs 550 kilos and is capable of handling the largest acetylene cylinders, which weigh 70 kg, and are 135 cm tall with the arm fully extended. The system can be operated by a single trained operator in cooperation with other firefighters. The

Figure 3.28. The firefighting robot – a rock-drilling machine to which has been added a gripper, three cameras and a wireless video link. The operator control unit is mounted on a sack truck.

operators handle the robot training on their own at the local fire station. The robot is transported on a trailer and the firefighters are scheduled so that the robot is available for service on call. The robot team of Södertörn's fire station service the entire Stockholm area.

3.6 CBRN Contamination Control

The analysis regarding CBRN contamination control was carried out by interviewing two officers involved with testing, development and training at the CBRN center of the Swedish Armed Forces[25]. Both respondents held the rank of captain in combination with a Master's degree in engineering. The two-hour interview was held with both respondents at the same time at the CBRN Test- and Training Center in Umeå (see fig. 3.29). The officers also provided a demonstration of current and future sensors. None of the officers had previous professional experience with robotics but they had a general knowledge of the progress of military robotics and were given a demonstration of an iRobot Packbot Scout during the visit. The interview was formulated to examine how a robot could contribute to the Light-role CBRN team of a battalion[26] on international missions. The objective of the Light-role CBRN team is to indicate hazards and, if applicable, secure evidence of the use of CBRN agents. Decontamination, other than of their own personnel and gear, is not a task for the team and was therefore not included in the discussion.

[25] 26 September 2006
[26] A battalion consists of approximately 1200 soldiers.

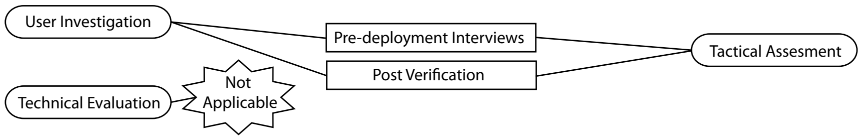

Figure 3.29. The various data collection methods and how they contributed to the study of CBRN teams.

3.7 Explosive Ordnance Disposal

The EOD inquiry was carried out by interviewing an army captain, a naval captain, and three senior members of the police bomb squads in Stockholm, Gothenburg, and Malmö. The inquiry (see fig. 3.30), which took place out at the Swedish EOD and Demining Center (SWEDEC) in Ekjsö, was carried out at the same time as an EOD robot course, on which the respondents were serving as instructors[27]. This provided an opportunity to observe a group of three police officers practicing clearing a car-bomb with a Remotec Andros robot (Remotec, 2007) (see fig. 2.1). Becoming an EOD robot operator entails a total of six months of EOD courses, three years of EOD service, and a one-week robot course.

The formal interview was carried out as an open group discussion with all five respondents for one hour. In addition, field interviews were carried out with the instructors and the course participants during the two-day visit. The survey focused on missions dealing with a single or a limited number of explosive items rather than large scale removal of unexploded ammunition or mines. The Andros robot is about to be replaced by the Allen Vanguard Defender (Allen Vanguard, 2007) (see fig. 2.9).

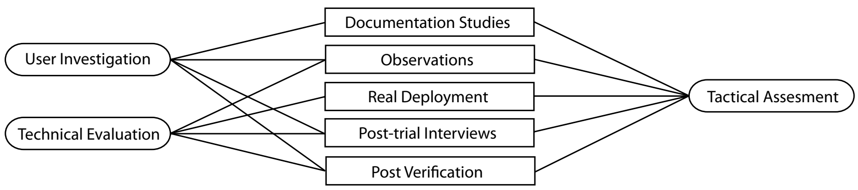

Figure 3.30. The various data collection methods and how they contributed to the investigations of EOD teams.

[27] 25-26 October 2006

Chapter 4

Results I – MOUT

This chapter presents the user characteristics as well as the tactical and technical findings from the MOUT trials. The presentation is initiated with a general description of the users in terms of common tasks, organization, methods and limitations. Then follow the results from initial attempts with the ATRV robot after which the results from the main trials of the Packbot within the MOUT company are presented. The results from the mapping experiment (see 3.1) are included in the description of Packbot deployment.

4.1 User Characteristics

Military operations in urban terrain may be one of the most challenging team tasks performed. Complexity, lack of information, personal risk, fatigue and pressure of time in possible combination with limitations in experience make the task highly demanding. Forces deployed in peace-keeping and peace enforcement missions may also be pressured by cultural differences, media coverage and ethical doubts. Compared to missions in field settings, urban operations often tend to be more fragmented without clear borders between civilians, enemies and allies (Krulak, 1999). The numerous possible hideouts and the difficulty in overviewing urban areas call for a large number of personnel to control an area even against small enemy forces. For example, to *seize* and *secure* a building such as the one displayed in fig. 3.11 would be a typical task for a MOUT company.

A company can be described as the smallest self-sufficient army unit in the sense that it has medical resources and supplies to last a around tree days, can handle vehicle towing and field repairs, and is given tactical responsibility for a defined area. Command is carried out by two captains with six to ten years' of experience. Only one is the formal commander, but in urban operations they often work in unison, one leading the soldiers moving on foot while the other manages the APCs. A MOUT company consists of three fighting platoons and a staff/supply platoon. A platoon is commanded by a lieutenant with three to six years' of experience who is assisted by a conscript sergeant. The platoon leaders and the assisting sergeants carry radios for communication with the company commanders and the APCs. A MOUT platoon consists of four squads, each with an APC. Each soldier has an area of expertise such as squad leader, machine gunner, sharp shooter, demolition expert, combat medic, APC commander, APC gunman, or APC driver. When moving on foot, the soldiers perform in pairs (*buddy system*) in order to provide mutual protection, assist during obstacle passing, and so on. Tasks that have to be solved in exposed settings are executed according to strict routines. For example, a soldier having a weapon malfunction calls out 'malfunction' and drops low in order to take cover as well as to visually inform the others about his inability to solve the current task. Meanwhile, the soldier's 'buddy' positions behind him or her as a lookout in order to offer protection until the problem has been resolved.

For transport in urban terrain the troops have the option to use APCs. In the event of hostile encounters the soldiers often leave the vehicles and continue their movement on foot through buildings in order to be sheltered and hidden. From then on all equipment has to be carried, which requires all gear to be compact, light, and rugged. Only the most necessary equipment and limited amounts of supplies can be brought along. Soldiers are, however, already heavily loaded and forced to leave important gear, supplies and water behind.

The combat vehicles are often left behind because they have limited mobility and constitute a relatively obvious target which, despite their armor cannot withstand the firepower of modern portable anti-tank weapons and mines. Normally a driver, a machine-gunner and an APC commander remain in the vehicle in order to perform medical evacuation, fire support, outflanks, etc. While moving on foot the soldiers have to be able to traverse obstructions, climb through windows and onto roofs.

Most indoor operations are carried out in twilight or darkness with either helmet-mounted night-vision goggles or powerful flashlight illumination. Both have their drawbacks. The night-vision goggles cognitively impair the wearer by limiting the field of view and eye movement, removing stereo vision, and obstructing rifle deployment (Sandberg, 2003). A flashlight, on the other hand, reveals the position of the user. A common solution, which takes the pros and cons of both into account, is to use the night-vision aids for stealth *reconnaissance*, and white light for armed action during which the requirement of perception and speed is prioritized.

Communication and distribution of information is challenged during urban operations. First, the conditions for voice communication are often poor due to physical factors and the necessity to operate in silence. Second, there is an aggravating factor due to the high stress level on the personnel. Third, the organization is strictly hierarchical so all information transfer and most decisions are handled through the chain of command. In addition, some of the leaders have to communicate on two different radio networks, one for subordinates and the other for superiors. However, units or individuals cut off from communication will continue to act according to the commander's outline plan.

To improve the information distribution, tests are currently in progress to equip every single soldier with a radio for inter-squad voice communication. The radios

Figure 4.1. Sketches are commonly used to hand over spatial information. In this case the company commander is briefing the platoon leaders.

have been shown to eliminate many of the communication problems related to the delivery of verbal messages, but much of the information is spatial and difficult to present through speech. The use of sketches is common when communicating face to face, and basic sign language is used for line-of-sight communication (see fig. 4.1). Trials are also being made to equip soldiers with night-vision goggles, wearable computers for GPS positioning, digital maps, aerial photographs or satellite images, digital cameras, and radio data networks for information sharing (Hoving, 2003; US Army, 2007b; Rheinmetall AG, 2007).

Despite communication difficulties the units are expected to perform swiftly and in synchronization. Predefined tactics help the soldiers anticipate how their own forces will act in situations when planning or communication is lacking. All basic military behaviors have been thoroughly defined and practiced in order to minimize reaction times, optimize efficiency, and cut the risk of fratricide. For example, at squad level it is defined in detail what equipment each soldier carries, which task each soldier performs, how the squad moves, who opens doors, who is the first to enter, how parallel activities are synchronized, and so on (see fig. 4.2). Established routines are not static but are continuously evaluated and refined. Evolution is, however, an incremental process performed over many years. Examples of predefined key behaviors relevant when considering UGVs are:

Reconnaissance – Gathering information through remote observation or by entering the specific area. Enemy encounter is avoided.

Combat reconnaissance – The same purpose as for *reconnaissance* but

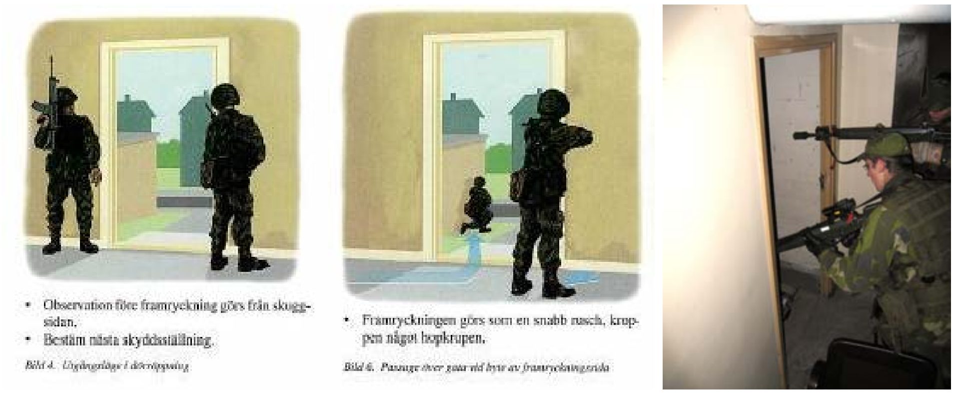

Figure 4.2. The military rely on well-defined and structured behaviors. The training manuals (illustrations to the left) describe in detail how common behaviors should be executed. The prescribed behaviors are strictly followed (right photo). The left-handed shooter is to the right of the opening and the right-handed shooter is on the left in order to be exposed as little as possible when aiming though the passage. Observation is carried out from the shaded side (the soldier on the right in the photo), advance from the opposite, in a slightly crouching position (the soldier on the left in the photo).

with the aim of pursuing into *attack* in case of an enemy encounter.

Attack – Offensive action through maneuvering and firing of weapons in order to hold, neutralize or force the enemy to surrender.

Seize – Taking control of an area with or without an enemy encounter. This includes ensuring that the area is free from enemies and establishing a defense.

Search – Defensive way to perform *seize*. Soldiers go through a building room by room without using any firepower. *Search* can be performed silently.

Cleanse – Offensive way to perform *seize*. Soldiers go through a building room by room with preventive use of hand grenades and rifle fire, i.e. throwing grenades and shooting into the next room before entering or even observing it. *Search* often precedes *cleanse* until enemies are encountered.

Break-in – More or less aggressive action to enter a building. Obvious entrances such as doors are avoided due to the risk of IEDs or ambush. Ladders or vehicles are regularly used to enter above ground floor (see fig. 4.3). Armored vehicles can be used to breach walls and provide massive fire support for soldiers on foot. *Break-ins* are initiated from a *safe spot* and are considered completed once the troops are in control of a *safe room* inside the building. Executing a *break-in* is a task for an entire platoon

Figure 4.3. *Break-in* performed through a window to avoid ambush or IEDs. One squad is entering (right), one is ready to go (center), and another is being briefed (left) by the platoon leader (pointing). The first goal after entering is to establish a *safe room.*

and is considered to be a very risky operation that has to be carried out with rapid intensity. *Break-ins* are regularly preceded by diversions.

In addition to predefining and practicing of fixed behaviors, the MOUT doctrine strongly emphasizes that only one task is conducted at a time. Individual soldiers or units are given only one objective at a time to avoid any ambiguity or mishaps due to mental overload. The high-risk, uncertainty and pressure of time have furthermore made the MOUT troops very aware of reliability, a phenomena also observed among police SWAT teams (Jones *et al.*, 2002). Being able to execute a task according to plan is favored over attempting something more advanced that may not work. Failure to carry out an outlined plan is considered a major tactical setback since one of the foundations of military doctrine is to be proactive rather than reactive to the enemy's actions. In fact, reliability along with the desire to move and respond to new situations swiftly is often considered more important than reducing risk (at least during training maneuvers). Often a task is so time-constrained that if it cannot be solved within certain limits, it does not need to be performed at all.

For international missions the enemy is expected to be technically less well-equipped and trained but possibly more experienced. Recent conflicts show an increased use of asymmetric measures or means violating international law, e.g. deploying snipers and suicide bombers, resorting to terror actions, and targeting civilians (Krulak, 1999). It is a well-established tactical fact that a defending force is better motivated and more willing to take risk, and also holds the advantage to fortify which requires a power balance of approximately one to four compared to the attacking force.

Likely tasks in international missions differ from those performed during soldier

Figure 4.4. A medicals' log written on a wall in the *safe room*. The ones in the left column are the enemies and the ones in the right are the own. The log keeps track of the priority for evacuation of the wounded. Abbreviations: "P1" – very urgent, "P2" – urgent, "P3" – not urgent, "P4" – dead or mortally wounded, "av/avtr/avtransporterad" – evacuated. This was the outcome of half a day of training maneuvers.

training. Despite a serious attitude and sometimes even frightful realism during the exercises, it is hard to reconstruct the true impact of casualties. The aim during soldier training is to get the most possible out of available resources and time. Training is, therefore, directed towards complex tasks, such as offensive, high-paced, and full-scale battles carried out in order to engage and, thereby, train, as many soldiers as possible. Routine duties such as surveillance or low-intensity conflicts receive less attention. During the study, the examined MOUT company normally trained two rather offensive *seize* missions per day, each causing 5-30 of their own wounded or killed (see fig. 4.4). This is not a likely level for international missions. Troops participating in international missions are reluctant to risk their own or civilian losses – a phenomenon that has also been pointed out in other countries (Sion, 2006). The need for training with less aggressive behaviors and no lethal weapons has been recognized.

The observed training maneuvers did not deal with the dilemma of IEDs or anti-personnel mines to any great extent, although such threats may be a significant problem in international missions. By October 2007 the casualty count of the coalition forces in Iraq shows 40% of deaths to have been caused by IEDs[1] (iCas-

[1] Close to 1800 persons.

uaties.org, 2007). High ambitions to obey international law during soldier training as well as unwillingness to spread knowledge of how to cause terror actions may be reasons for not including IEDs in the training of conscript soldiers[2].

User Characteristics in Summary

Military units can be regarded as archetypically mechanistic in terms of organization theory (Burns and Stalker, 1994)[3] The investigated MOUT company has a well-defined hierarchy in terms of command, information flow, competence and areas of specialty. In a military context, the mechanistic organization is however not a consequence of it residing in a particularly stable surrounding such suggested to be the normal for mechanistic industrial ventures. Instead, the strict organization within the military is a response to high surrounding uncertainties in combination with the need to enable instant replacement of both individuals and units with maintained level of performance. At the lower organizational levels of MOUT (company, platoon, and squad) the doctrine enforces proactive actions which tend to force the course of events onto states onto which predefined and practiced behaviors can be applied. The mechanistic control strategy applies as long as the military chain of command and the information flow are intact. In the event of failure, the organic trait of distributed command applies as isolated units or soldiers will continue to act according to their commander's intentions. MOUTs are complex team tasks, and procedures are highly defined and thoroughly practiced in order to enable synchronized actions even when coordination is absent. Time is often a critical issue and the means of communication are sparse.

The MOUT troops regularly leave the APCs and continue their movement through buildings on foot. Alternative entrances such as windows are preferred to avoid ambush or IEDs. Weight is a critical issue as the soldiers are already heavily loaded. The units are expected to perform their tasks no matter the type of premises, level of destruction, weather conditions or time of day. Massive weapon deployment and rapid action are used to *seize* premises that are known to be or suspected of being held by an enemy. This increases the risk of civilian casualties. Non-lethal weapons and methods are desired although the training maneuvers are performed more aggressively and at higher pace than what is expected in international missions. Tactics are typically refined through small iterations over long periods of time. Direct enemy encounter is the focus during training maneuvers although the Iraq conflict indicates indirect measures such as IEDs as causing the largest death toll. The main user characteristics are also summarized in table 4.1.

[2] Learning how to neutralize IEDs would also mean learning how to rig them.

[3] Burns and Stalker define two opposite types of organizations: mechanistic and organic. While mechanistic ones are organized in a pyramid structure and strongly hierarchal, the organic ones have a network structure with distributed command and informal information flows.

Table 4.1. User characteristics in summary

Area of concern	Main features
Primary tasks	To take and maintain control of urban areas. Today's tactics are characterized as either rather defensive (the use of violence is often highly restricted prior to interception) or highly aggressive (post-breakout of violence motivated by self defense); non-lethal alternatives are desired to enable more nuanced responses.
Environment	Mainly urban, likely in destruction. Day and night, all weather and climate.
Organization	Hierarchical top-down management with well defined information flows and areas of competence. Distributed control according to commander's intentions as a backup.
Work methods	Predefined, detailed, and well practiced team behaviors.
Command, communication, and coordination Risks	IEDs/mines and hostile fire.
Main limitations	Time, workload, communication/synchronization and night-vision capability.
Demands on gear	Reliable, rugged, man-portable, and light weight. The power endurance for electronic gear such as radios is several hours. Routines for battery replacement and changing enabling continuous operation exists.

4.2 Initial Attempts

As previously described (see 3.2), the conditions during the initial attempts did not provide an opportunity for extensive user investigation. Many robot "novices" reacted to the red color and the non-rugged appearance of the ATRV. "Shouldn't it be green?" or "is it bullet proof?" were common types of comments. The rather limited findings included here are provided as indications rather than in-depth discoveries.

The Robot Vehicle

Robotic vehicles for outside exploration will be required to have at least similar terrain ability and endurance as other military vehicles. UGVs also need to be able to move at the same speed as the military vehicles in order to fit into the broad range of MOUT scenarios. It should also be considered that the logistics issues of introducing yet another vehicle type into a military unit are not to be underestimated. Basing vehicle-sized robotic platforms on common vehicle types, or at least using components from common vehicles as far as possible would be very advantageous.

The User Interface

The general opinion of the officers was that interaction with the ATRV was intuitive and easy to learn. The main setbacks seemed to be caused by the lack of status feedback and delay. Delays were particularly restrictive during tele-operation. The users expected immediate reaction while manually driving the robot. When a delay in response occurred they often kept repeating the same command, which accumulated in the buffer and caused overreaction once executed. As for most applications, it is preferable to reduce delays, and when delays are unavoidable, the user must be notified. When growing more experienced with the system, users adapted to the delays, making them less restrictive.

While touch screens allow for flexibility in user interface design, they do not provide haptic feedback to support localization (finding controls without looking at the OCU) and positioning (feeling the state of a button, the position of a slider, etc.) of controls the way mechanical controls do. Sound or vibrations could, to some extent, be used for compensation. Visual feedback, such as highlighting the button that had been pressed on the touch screen interface, did not prove feasible for robot operation as the operators' visual attention was not constantly directed towards the OCU.

The target areas of the touch screen controls should be kept large enough to permit operation with the fingertips rather than with a pointer pen. The screen of the iPAQ was inadequate for use in direct sunlight and was too bright for night-time operation. LCD screens need to have different display modes for daylight and night-time (such as regularly featured on for example GPS devices).

Autonomous Behaviors

Apart from the line-of-sight tele-operation mode, the ATRV was entirely autonomous and the system provided little feedback to the operator during execution. From a tactical perspective the commanders will desire the option to receive information about the system's progress and to be able to redirect the mission at any point in time[4].

A *Road Follow* or *Follow-Me* behavior needs to be very robust in order to be useful in real missions. An end-user expects issues such as changing light conditions, limited visibility (e.g. fog, dust, etc.), deviations, slippage, obstacles, other traffic, humans and animals to be considered.

The maps and plans normally used by the military differ from those generated with laser SLAM[5] (see fig. 4.5 and 4.6). SLAM can only depict the structures (e.g. facades) that can be covered by the sensors, unobserved areas appear as blank spots. Traditional maps or drawings, on the other hand cover a defined area completely.

[4] This will require constantly also having autonomous UGVs in radio cover.

[5] Simultaneous Localization And Mapping. The currently most efficient SLAM is achieved with laser scanners.

Figure 4.5. The ATRV robot during autonomous exploration at the military training facilities in Kungsängen.

Regular maps typically have a scale down to 1:10 000 while SLAM enables for a significantly higher resolution. In addition, SLAM allows depiction in 3D while traditional maps are abstracted to 2D. A facility to enrich laser maps with visual information (i.e. overlaying digital images onto a 3D laser model) would provide valuable contextual information.

Penetrating sensors, such as radar and X-rays, enable tactically valuable features but require appropriate visualization to field-workers. Over all, the novel properties of the information provided by robot technology will require the user to develop and learn new skills. A way to automatically merge information from new and traditional sources (robots, satellites or printed maps) is a highly desired feature.

When considering sensing, it has to be considered that active sensors such as radar or laser range finders will be relentlessly revealing on the battlefield; modern main battle tanks are already equipped with laser detectors. The development of autonomous systems based on active sensing for military application cannot simply be pursued without taking the stealth issue into consideration.

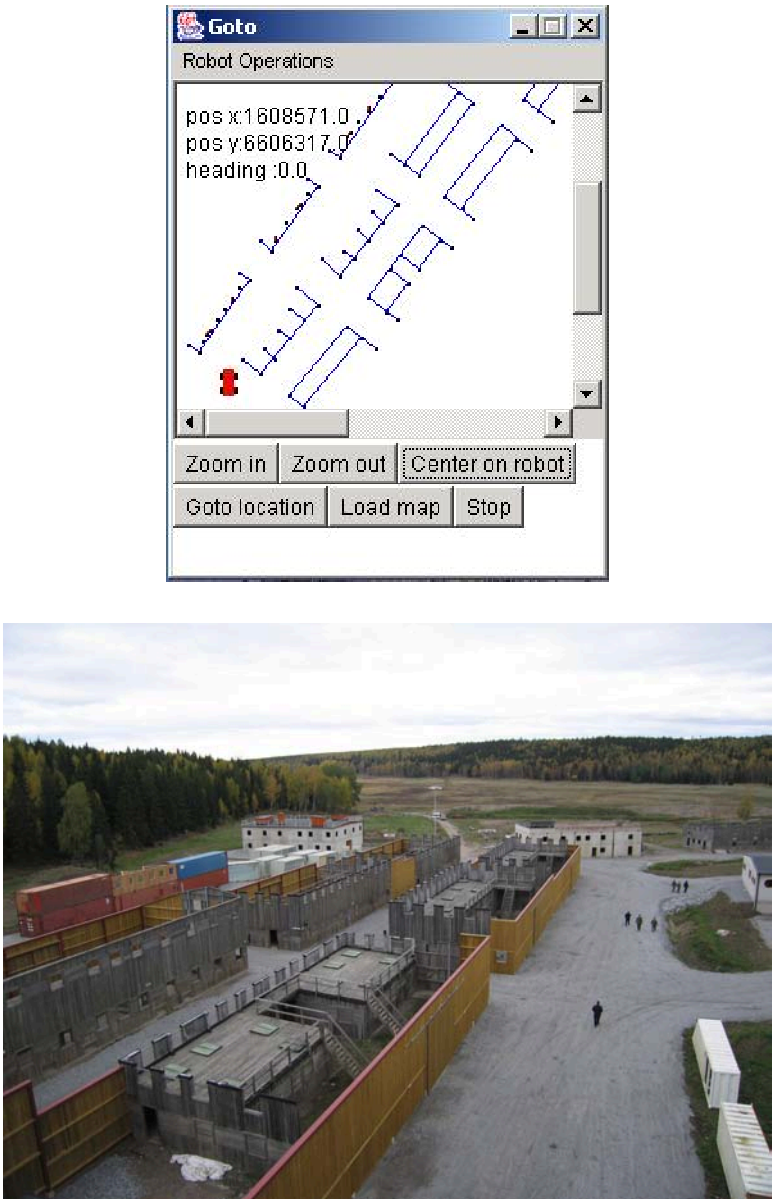

Figure 4.6. An autonomously produced map (top) of the military training facilities at Stora Sätra Kungsängen (bottom). The brighter facades did not exist at the point in time when the map was produced. The building with the square cut-out in the center of the map is the one appearing nearest in the photo.

4.3 Main Trials

This section includes the results concerning user assessment of the Packbot Scout within the MOUT unit during the pre- and main studies[6]. In addition, results from the mapping experiment are included (see 3.3).

Operator Control and Situational Awareness

It was found that the operators' ability to control and take advantage of a robot system passed through a number of perceptual stages (1-4). In general, the earlier steps have to be mastered before the on following.

1. *Motor level* – The first stage contains the handling of the user interface controls and basic operation of the robot. During this stage the operator's perception is focused on the vehicle's responses to the drive commands and on gaining a sense of the dynamic properties of the robot. Frequent problems during this stage include collision, uneven speed control and perspective error, i.e. confusion of left and right (during line-of-sight operation). To give novice operators the chance to observe the properties and drive-command responses it is beneficial to start training using line-of-sight.

2. *Physical interpretation* – Next, the operator is able to start controlling the vehicle out of sight. While doing this, the operator has to rely on the video feedback provided through the user interface. The step from line-of-sight to video feedback operation significantly reduces both visual information and other clues such as audio feedback. Reduced feedback significantly complicates tele-operation, especially in rough terrain (Lundberg and Christensen, 2007). Human assimilation of the video feedback is carried out in different degrees of depth. The primary stage is to comprehend the physical extent of objects shown through video by interpreting their geometrical outline. This includes learning the optical properties of the camera (for example wide-angle) and adjusting to the perspective of its position (low compared to human vision). Mastering the skill of physical interpretation enables the operator to estimate the extent of the surroundings in order to drive the robot around without colliding[7]. Reaching this stage also enables the operator to combine knowledge about how the robot, observed through the OCU, ought to behave according to a given drive command. A difference between the given drive commands and the video feedback indicates if the robot, for example, is stuck or skidding. With practice the driver develops the ability to perceive and overcome such problems when possible.

3. *Navigation* – Once the operator is able to interpret the information provided by the OCU, he or she can begin to continuously track the surroundings in

[6] See fig. 3.1

[7] Behaviors denoted as *wander* and *collision avoidance* in autonomous robotics.

relation to the motion of the robot in order to create a mental model of the surroundings[8]. Even after fully mastering the skill of observing the outline of premises, a human being will have limitations as to the amount of spatial information that can be kept in mind at the same time.

4. *Contextual interpretation* – As the execution of previous steps develops into more or less autonomous behaviors on the part of the operator, mental resources are freed to interpret and make use of contextual clues[9]. This includes blending information from the previous levels with knowledge with anticipations based on previous knowledge and experience. For example what size rooms are likely to be encountered in different types of buildings. Contextual information (such as a horizon) also enables the operator to monitor the robot's state, for example, if objects appear upside down the robot may have rolled over. Contextual interpretation also permits localization of and interaction with objects. Further, mastering this level permits understanding the state of the surroundings. A bulging wall, for example, may not merely represent a curved obstacle but can also be interpreted as a sign that the building is about to collapse. A disordered environment is not just a cluttered space for navigation, but also gives a clue about what may have happened in the past, and so on.

The prospect of refined SA (see 2.5) depends strongly on the amount and quality of the information provided. Important technical parameters include resolution, frame rate, latency, field of view and perspective. Demands on the human robot interface increase along with the perceptual stages. Hence driving a robot within line-of-sight does not require a lot of support or OCU-feedback whereas the later stages are very hard to achieve to the same extent as when being on the spot in person. Performing well at the higher levels will demand multimodal approaches and semi-autonomous support far beyond what is provided by the pure video streaming in systems available today.

Analogously it was found that demands on the operator vary with the knowledge of the surroundings explored with the robot. The operators could, for example, more easily anticipate the layout of previously familiar types of premises, such as residential buildings compared to industrial facilities. Absence of prior knowledge about what to expect increases the level of uncertainty and thus poses higher demands both on the operator and the user interface design.

It is important to be aware of the level of situational awareness a robot system is capable of providing. According to the presented sequence, there may, for example, be a distinctive boundary between using a robot to patrol previously known surroundings, as compared to working in unknown areas. Similarly it may be possible for an operator to explore the physical outline of a building, whereas understanding

[8]Such as in SLAM

[9]Carrying out contextual interpretation is very challenging tasks for unmanned systems to perform.

the contextual clues of the setting may be significantly harder. It is easy to mistakenly disregard the limitations within the perceptual stages as they pose hardly any problems for humans during first hands experiences (not through a robot). Doing so may generate seriously erroneous anticipation when estimating the tactical value of robot systems.

Tactical Results

Organization and command

At the end of the main study 83% of the users were of the opinion that every MOUT platoon should be equipped with one Packbot[10] (i.e. three systems per company). Having the robot systems as a standard part of the platoon, instead of as a resource to which access is allowed to from time to time, largely influences execution efficiency. It was considered that a MOUT robot, in general, has to be accessible within a few minutes since the tactical window of opportunity does not allow for longer delays. The information gained with the robot is of most value to the soldiers about to enter the area that has been explored, i.e. the unit that is deploying the UGV will be also the ones benefiting from it[11]. As soon as any of the team-members enter the premise, they will gain better control through their own senses and means (weapons) than with the robot. Any information about an enemy presence is typically only valid for a short period of time, as revealed enemies are bound to change their position. The robot operator needs to be at the site of exploration to rapidly grasp the overall setting in order to physically handle the robot and be able to pass on the gained information quickly.

Operating and handling the robot system proved to be a two-person task due to both physical and mental workload issues. To a great extent, the mental workload imposed isolates the operator from the surroundings although this can, just as for other mentally demanding tasks, be handled through the *buddy system* (see fig. 4.8). While the role of an assistant can be performed by any soldier given some additional training, the operator requires at least one week of individual training[12]. The operator needs to have the tactical and verbal skills of a squad leader in order to understand the tactical situation and to communicate gained information to others.

As mentioned, the military is accustomed to tasks that have to be performed in support of others, so the ratio of two persons per robot does not seem to be of critical concern. On the contrary, the MOUT doctrine states that only one task should be solved at a time. It is accordingly not applicable to have one

[10] *How many systems do you believe to be appropriate for a MOUT company?*
□ *One per company*
□ *One per platoon*
□ *One per squad*

[11] Compared to for example UAVs, which in many cases are operated by others than those taking part of the information gained by the system.

[12] Covering the 1 – *Basic Level* and 2 – *Map and Search Level* described in 3.3.

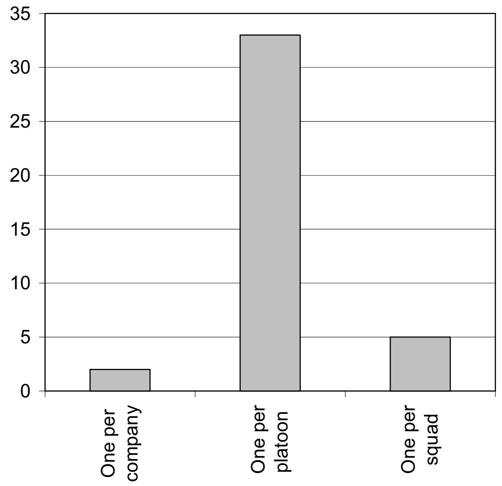

Figure 4.7. The distribution of replies regarding how many robots the company ought to be equipped with (see footnote 10).

Figure 4.8. The mental workload imposed isolates the operator from the surroundings. This can, just as for other mentally demanding tasks, be handled through the *buddy system*.

Figure 4.9. The heaviest lifts occur when the soldiers lift each other during medical evacuation.

operator deploying several systems simultaneously as is often suggested in research concerning autonomy (Jones and Lenser, 2006).

The robot was one of the heavier pieces of equipment handled, although occasionally, one soldier drags or carries another wounded soldier who weighs at least four times as much as the Packbot (see fig. 4.9). The robot's weight and size reduces the ability to perform dynamic moves such as running and jumping. The extra weight and size also cause problems while passing narrows and crawling in cover. Furthermore, falling over with the extra weight increases the risk of injury. The robot crew need to be physically stronger, more motivated, and more alert than the average soldier while moving on foot. Although the robot and the OCU could be carried by one person, a pair moves with speed and endurance better corresponding to the rest of the troops.

Similar to other company-shared resources, the commander sets a standard to submit the robot system to the platoon momentarily having the highest demand (see fig. 4.10, 4.11). Platoon leaders in charge of the robot system most commonly assigned it to one of the squad leaders, who in turn acquired the information. Alternatively, the leaders had the soldiers about to enter the area explored with the UGV cooperate with the operator directly. After fulfilling a platoon's needs, the system was released and relocated to the company's post for medical evacuation to await the next mission. Having the robot and the operators assigned to varying units also involved having them transported by different APCs. This proved to

Figure 4.10. The platoon leader (right) giving orders to a squad ready to enter an unknown area. The robot does not currently have a task and the robot operator is therefore to enter as the last person.

cause logistical problems since the vehicles were already fully loaded with gear and supplies (see fig. 4.12). Being able to transport and preferably launch the robot from the outside of the APCs would be valuable.

Specification of Tactical Behaviors

A MOUT scout robot needs to be closely integrated with the deploying unit. Leaders at all levels of the company, as well as the individual soldiers, have to adapt and practice their tactics to accommodate robot deployment. Experience is required in order to accurately decide the situations in which the UGV should be deployed; how the mission should be conducted; how long a robot mission will likely last; what terrain the robot can handle; and what information the system is capable to provide. The trials meant to specify the robot operation in as much detail as other MOUT behaviors. This included defining the operator's tasks as well as working out how squad, platoon and company commanders should reason regarding when and how to deploy the robot. The level of detail is indicated by the following examples:

Operator level – Robot exploration should be carried out along walls that provide a reference for navigation. Deviations from walls should be executed in a perpendicular pattern; the compass can

Figure 4.11. The Packbot is sent off to explore a region. The DFWES sensors can be seen on the soldiers helmet and shoulder.

Figure 4.12. Inside view of an APC. The vehicles are already fully loaded. The possibility to launch the robot without opening the APC is of interest.

be used for support although the risk of local deviation due to metal has to be considered. The point at which the wall is temporarily abandoned should be memorized to facilitate return. This methodology is especially vital when exploring larger areas.

Squad level – Since time will only allow for one report, the exploration should be completed before passing on information. However, in the event that immediate progress is necessary, the operator must be prepared to interrupt the exploration to report current findings.

Platoon level – The robot can be deployed for tasks that are normally performed with backup from the rest of the platoon. This enables exploration beyond the point when all soldiers are occupied guarding already seized areas.

Company level – The robot can be used for high-risk *reconnaissance* or for situations in which *cleanse* is not feasible, for example, because of possible presence of civilians.

Executed Scenarios

During the training maneuvers the robot was deployed on 2-10 occasions per day[13]. Figure 4.13 displays the distribution of the different types of missions according to the post-trial questionnaire[14]

The missions reported most frequently were: *reconnaissance* inside buildings 37%, investigation of *break-in* points 24%, and *mapping* 21%. The flashlight and Claymore payloads were deployed 8% and 7%, respectively. When considering this distribution, it has to be taken into account that the payloads were not available until the two last maneuvers of the main study.

Methods for Deployment

Robot *reconnaissance* was typically initiated from a *safe spot* where the squad could make a short stop under cover. From the *safe spot* the squad or platoon leader ordered the operator to perform the search with specifics as to what area

[13]The robot was part of the training maneuvers for 16 days during the main trials, see Sec:Outline

[14]*Describe the different scenarios you have experienced during the UGV-trials...Select the type of scenario from the following...:*
A. Reconnaissance of break-in point
B Reconnaissance in rooms or corridors
C Illumination with flashlight
D Mapping
E Deployment of Claymore mine
F Surprise or mislead
(The response-fields were: Scenario type (A-F), number of times, in what exercise area the mission occurred, the course of event, as well as pros and cons).

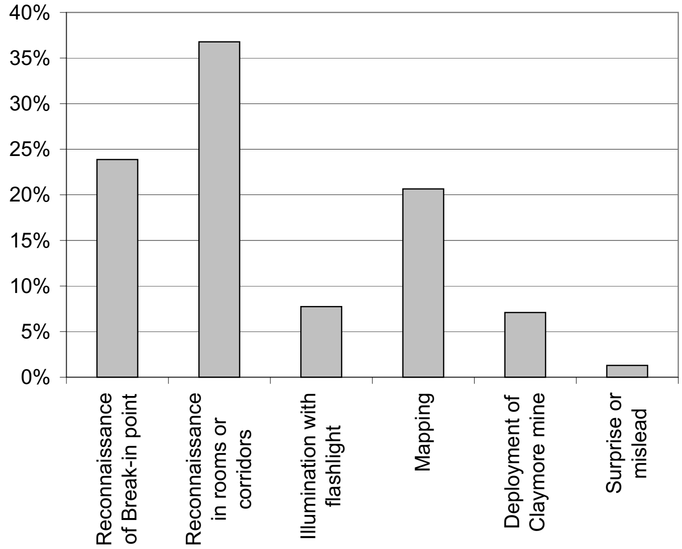

Figure 4.13. The distribution (%) of the different scenarios reported in the questionnaire (see footnote 14).

to explore, the time available, and who to report to. It was beneficial to have the operator attend the company and platoon briefings to gain general insight into the tactics. Attending the briefings also enabled the operator to suggest suitable deployment of the UGV.

Robot exploration was carried out short steps at a time to avoid losing radio contact, and to ensure the acquired information was up to date (see fig. 4.14). The tentative exploration also enabled the commanders to keep up the momentum. It additionally reduced the need for soldiers to memorize large amounts of information. The successive method was also motivated by the commanders' desires to perform immediate action towards enemies encountered, thereby minimizing the forewarning effects of the robot. Consequently, exploration was carried out one or two rooms ahead and ideally produced a suitable *safe spot* for the soldiers to advance to.

Handing over spatial information is an important part of using the UGV for *reconnaissance* and *mapping*. The operator displayed sketches of all but very simple premises on the small whiteboard (see fig. 4.15). The sketching was best carried out incrementally, 1-3 walls or doors at a time. Attempts to keep too much information in mind easily led to information loss. In the interest of time and clarity, only very basic information, such as walls, doors, and windows, was depicted. When showing the sketch, the operator added a few keywords describing the character of the environment and any people observed. Sketching also helped the operator better grasp the layout, i.e. supported the attaining of the third perceptual stage (see 4.3).

Figure 4.14. Robot exploration was carried out taking short steps at a time so as to avoid losing radio contact and to be sure the acquired information was up to date.

Non-operators looking at the view image provided by the robot had difficulty assimilating the context of the explored region, i.e. they were unable to reach the third perceptual stage. One likely reason is that passive observers do not have the operator's motor notion of the joystick commands (first perceptual stage). Constant attention had to be given to the robot's camera view in order to understand the spatial layout (see fig. 4.16). If the operator explained the robot's current position (preferably with a sketch), however, the camera view could be used to point out specific observations. Unfortunately, the interface design did not allow for snapshot images to be taken and stored for later viewing.

In order to increase the distribution of information, a test was carried out to equip the squad leader with a separate handheld OCU so that he could monitor the robot's camera while the operator was driving, without having to crowd around the same device or even be in the same location. In most cases, the leaders did not have the opportunity to continuously follow the robot's progress on the PDA. Instead they just wanted to be briefed on particular findings. In these cases, the operator had to spend considerable time explaining where the point of interest was located since only he knew the path driven to get there. Hence, it would be advantageous if

Figure 4.15. A small whiteboard attached to the OCU laptop lid with Velcro enabled the robot operator to describe the explored region to the soldiers about to enter with a simple sketch.

Figure 4.16. The *reconnaissance* squad using the PDA and the Packbot to explore the next section to advance through. The squad leader (lower right) is observing the OCU over the shoulder of the operator. Handling the robot prevents the operator from attending to his normal task (in this case, machine gunner).

the robot system could produce a map and have the facility to save video or images.

In the event an enemy encounter is likely, the entering team received more detailed information from the robot operator. If interference was not expected, the squad or platoon leaders were satisfied to know that nothing suspicious had been observed. Thus, it is initially of more interest to identify threats such as enemies or IEDs than to receive a spatial outline. The soldiers did not always follow the path of the robot, both for physical and tactical reasons. For example, the robot could be used to enter through openings too narrow for a person. Or, if moving between stories, the robot could be lowered by rope or use another set of stairs. When the platoon decided to advance in another direction, the robot could be used for continued exploration of the excluded region. According to MOUT doctrine, a platoon only expands in one direction at a time to avoid fratricide and maintain a focused strike force. The robot thus allowed for a change in doctrine.

If given enough time, the operators were able to make fairly accurate observations of the areas explored with the robot (see fig. 4.17). Areas indicated but not open to exploration, such as rooms behind closed doors, however, tended to be neglected and forgotten. The mapping experiment (see 3.3 and appendix A) showed robot mapping taking, on average, 96% longer and resulting in 44% more errors compared to manual mapping. Robot users tended to overestimate dimensions by an average of 16% while non-robot users only made an average overestimation of 1%. Further, the robot users on average had a 69% larger standard deviation in their dimensional estimations and on average made 123% more logical errors during the test. However, it was shown by high-performing robot operators that it may be possible to decrease time consumption and mean error. The results are likely to be valid for situations with similar user-interface characteristics, maneuverability, the surrounding environment and the training level.

From a tactical aspect the approximate layout and character of the premises is of main interest; dimensions do not need to be highly accurate. Other information of interest includes appropriate positions for cover and strategic fire, influenced, among other things, by the material and thickness of walls, doors, windows, and other objects in the area. The true effects of ammunition and scatter are diminished during training with blank ammunition. Soldiers tend to seek cover behind objects which would in reality not withstand small arms fire and shrapnel. Improvements in the Direct Fire Weapon Effects Simulator system are currently under implementation (by equipping buildings with sensors and actuators) in order to model this aspect with more accuracy. Training facilities are also being equipped with video and position tracking devices for soldiers and vehicles. It is important to also integrate these systems on robots since the user, at least in this case, spends more time practicing than performing real missions.

A hostile encounter probably means loss of the robot in return for decreasing personal risk. The soldiers not only concluded that the robot could decrease danger, but also argued that it could be used as an alternative to hand grenades and rifle fire during *cleanse* operations – an ability that would decrease the amount of ammunition required and minimize accidental harm to civilians and infrastructure. One

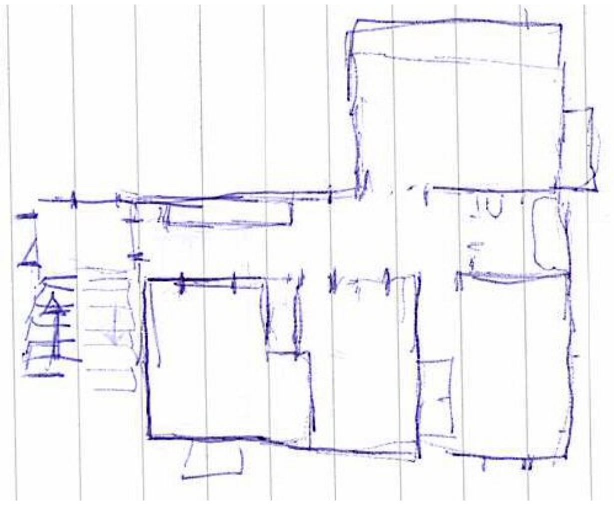

Figure 4.17. The operators were able to make fairly accurate sketches of areas they explored by means of the robot, in this case a two-bedroom apartment. While it took the robot operator 18 minutes to do this sketch, it would only take the soldiers a couple of minutes to perform the *search* manually.

of the platoon leaders pointed out that the robot could save enemy lives by opening for negotiation with the enemy in situations traditionally handled with brute force. Voice communication through the robot would enable alternative solutions to hostage situations, threatening crowds, and assisting wounded personnel.

The tactical significance of the robot dramatically changed when given lethal ability, turning it into a tool for breaking up entrenched situations or directing action against enemies encountered during exploration. Weaponizing the robot also added the possibility to use it for deterrent, threatening or misleading purposes. Correct identification of friends, foes and civilians is a crucial aspect during weapon deployment. This was a demand that could not be met with the quality of video feedback provided from the Packbot Scout. The Claymore mine could, therefore, only be deployed in areas certain only to hold enemy combatants, i.e. it was essential to be assured that none of one's own troops or civilians were in the area (something that cannot be done reliably with the Packbot due to limitations of resolution and field of view).

The flashlight payload was used to evaluate the benefit of personnel not having to hold the light themselves. The system was deployed on a few occasions, but never during an enemy encounter. The UGV was not deployed to trigger anti-personnel mines or trip-wired devices, as this threat was not included in the maneuvers. Trials were, however, made to visually identify IEDs during individual operator training. IEDs at floor level could occasionally be identified from within a few meters (see fig. 4.18). Higher-placed objects were hard for the operator to spot.

Figure 4.18. Trials were made to use the Packbot to locate IEDs. IEDs at floor level could occasionally be identified from within a few meters. The glare in the video is caused by the IR illuminator at close range.

Benefits

Multi-role capabilities are desired to enable frequent deployment. This is in order to justify the added workload the robot entails for the MOUT personnel. The complexity of payloads ranges from simple solutions such as two-way audio or fire circuits[15], to payloads requiring real-time data processing, or high speed data transmission to the user-interface.

The trial period did not permit the complete development, practicing and evaluation of the targeted scenarios. The respondents were therefore asked to estimate the benefit of the tested scenarios given that full implementation would have been carried out. 85% believed that the system could be deployed 7-10 times or more during a company attack of the type performed during training[16]. None of the respondents expected the robot to be used less than four times per attack (see fig. 4.19).

Figure 4.21 displays the estimated benefits from a UGV in the tested missions[17]. Of the 13 alternatives *5, 8, 10, 12 and 13* were never attempted during the training

[15] A fire circuit is a standard feature on EOD robots that enables the operator to control a binary switch on the robot. The switch is normally used to fire the disruptor gun, but it may also be used to turn on/off any other payload mounted on the robot.

[16] *Rate how many times per company attack the UGV-system could have been deployed if each platoon had one system in use.*
☐ *0-3 times for the entire company*
☐ *4-6 times for the entire company*
☐ *7-10 times for the entire company*
☐ *11-15 times for the entire company*
☐ *16 + times for the entire company*
(Two company attacks were carried out regularly per day during the maneuvers)

[17] *Evaluate what benefit the robot you have been testing would have in the following missions if the tactics for this were fully developed and practiced....*

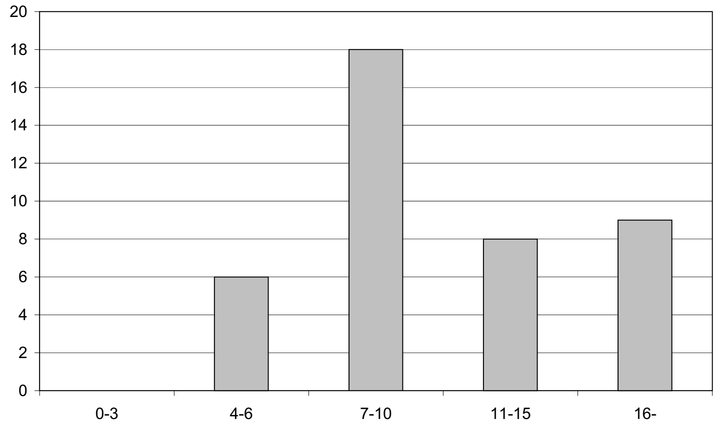

Figure 4.19. The distribution of estimated deployment frequency during a company attack if each platoon had a system (see footnote 16).

maneuvers. The distribution of the responses for two of the topics, *1* and *10*, is displayed in fig. 4.20. As can be seen for question *1*, the response was fairly unanimous which indicates that this mission was valuable. The responses to question *10* do not, on the other hand, reveal unanimity. In fig. 4.21 the unanimous answers to question *1* appear with a narrow interquartile range and a mean value close to the end of the scale. Replies to question *10* show a longer interquartile range and a mean that does not indicate such a distinct result.

Of the tasks that were actually tested, weapons deployment, together with *reconnaissance*, was the application considered to be of the most value. The clearing of mines and IEDs was estimated to be an application offering great potential.

1. Reconnaissance and mapping of break-in points: the robot was considered for use in order to closely investigate the *break-in* point, which is normally carried out visually from a distance. Being better informed enables the soldiers to enter faster and more precisely. Robot exploration must, however, be carried out unseen

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1. Reconnaissance and mapping of break-in points
2. Reconnaissance and mapping of rooms or corridors
3. Reconnaissance and mapping around street corners and along streets
4. Surveillance indoors
5. Surveillance outdoors
6. Deployment of area-covering weapons such as Claymore mines
7. Surprise or threat
8. Performing diversion
9. Illumination
10. Inspection, for example under vehicles
11. Transport of for example ammunition between firing positions
12. Clearing of anti-personnel mines or trip-wired devices
13. CBRN indication
(Replies were given on a five point scale and a text field was provided as an option for comments.)

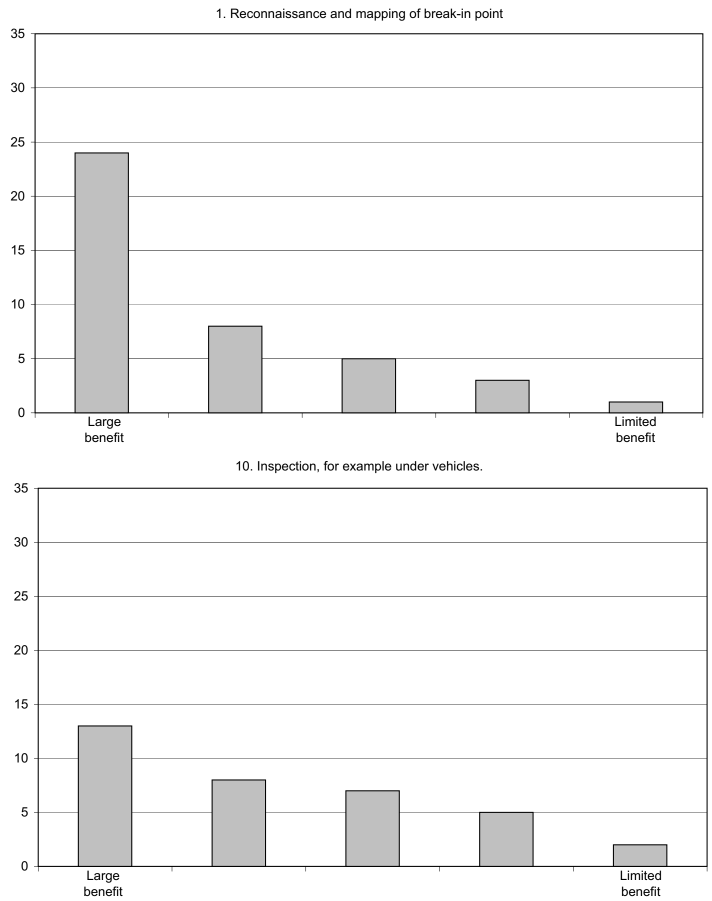

Figure 4.20. The distribution behind the mean values and interquartile ranges of questions 1 and 10 are displayed in fig. 4.21. The x-axis corresponds to the five point scale while the y-axis indicates the number of replies given. These two diagrams are included to exemplify the distribution behind the mean and interquartile range displayed in other diagrams.

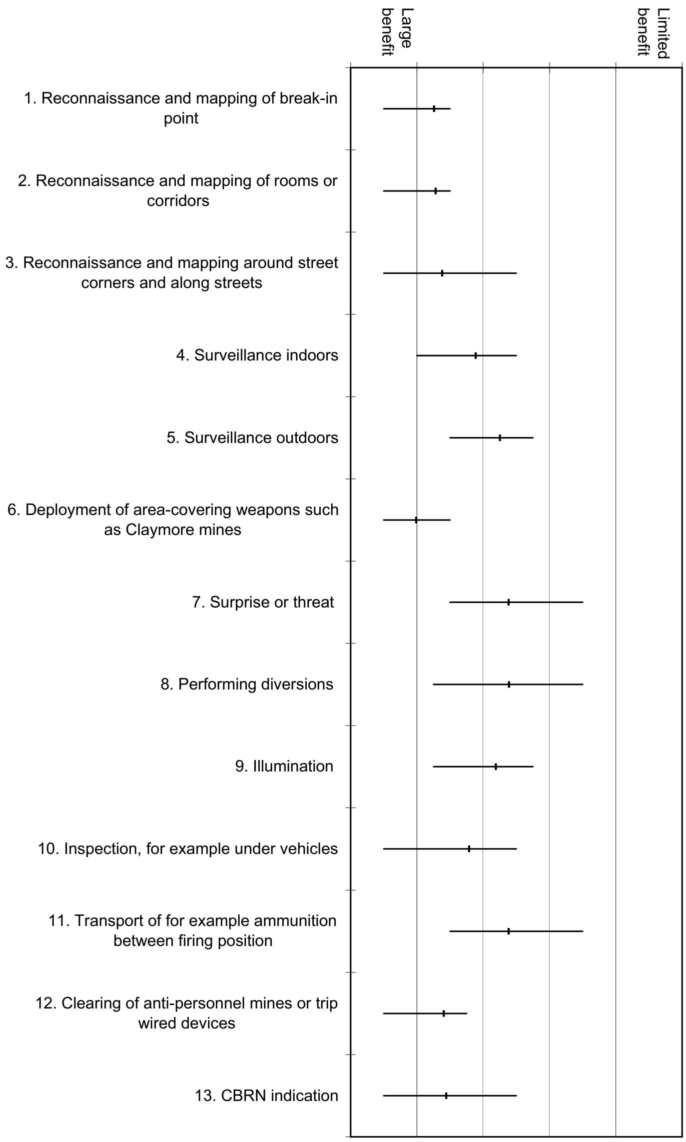

Figure 4.21. Estimated benefits for different tasks (see footnote 17). Dots indicate the mean value and whiskers show the interquartile range.

not to reveal the unit's intent since this would do more harm than good. The skeptical responders commented that using the robot would decrease the pace of the mission. It was also pointed out that the current radio range restricted the stand-off distance so that the investigation would most often have to rely on traditional methods. Off-road ability and noise were also mentioned as restricting the current system in this task.

2. Reconnaissance and the mapping of rooms or corridors: the robot was considered to be useful for exploration in advance of entering unknown premises. It could provide information about the layout, presence of people, and possibly enable avoiding IEDs. Again the robot was pointed out as likely to slow down the troops' advance. The risk that the robot may give the enemy advance notice is, on the other hand, less than for *break-in*, since the enemy is likely to have noticed that the building is being searched.

6. Deployment of area-covering weapons such as Claymore mines: having a weapon on the robot would permit direct action against an enemy encountered during exploration or to target an enemy entrenched at a known location. The latter would in practice probably entail losing the robot. Being able to have the robot take over some of the most dangerous fighting tasks was considered to be highly valuable. The high cost of the robot worried many of the respondents.

12. Clearing of anti-personnel mines or trip-wired devices: as detection is difficult, threats such as mines or IEDs can scarcely be identified beforehand. Even if detected, regular infantry units do not possess the special gear or skills to deal with IEDs. Instead they attempt to find a way around detected hazards or call in an EOD team to clear the way. It was considered that using the robot as a pre-runner that triggers auto-detonated weapons could significantly decrease the risk to soldiers (each such mission would entail losing a robot). Once more the cost was brought up, as this mission would have a ratio of one-to-one.

None of the respondents reported strong opinions against using robots as weapons[18] On the contrary, 79% replied that they had no objections to doing so and none of the respondents replied being strictly against (see fig. 4.22). Ten out of the 41 respondents did, however, comment that their opinion only applied as long as the fire command was executed by a human (not autonomous/automatic).

The tests were performed on maneuvers intensified both as to risk and time. To explore the offset, the test participants were asked to value the benefits for different types of operations likely for military forces in the European Union[19] (Ortega, 2005).

[18] *Do you think that using weaponized robots is unethical?* (Replies were given on a five point scale.)

[19] *Rate the value of the UGV for the following types of international operations...:*
1. Separation of parties by force, crisis management, peace enforcing operations
2. Conflict prevention, disarming, and confiscation operations

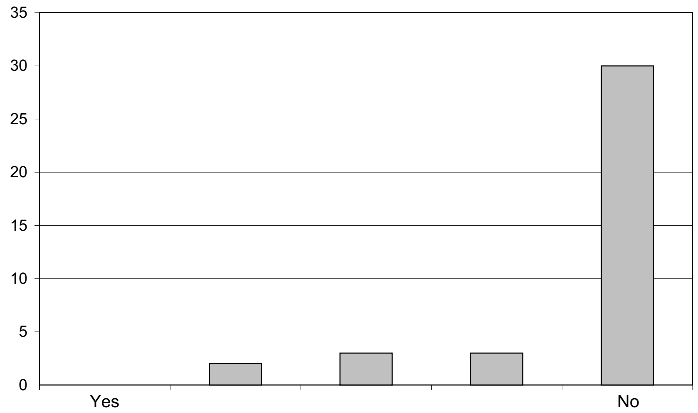

Figure 4.22. The results of replies concerning the ethics of weaponizing robots (see footnote 18). The y-axis shows the number of replies given on a five-point scale (x-axis).

Of the four types, the training maneuvers attended mostly resemble the most aggressive ones: *separation of parties by force, crisis management, peace enforcement operations*. These, together with *conflict prevention, disarming and confiscation operations*, were also the ones believed to be most suitable for UGV deployment (see fig. 4.23).

The final question of the questionnaire asked for general comments. Eleven people replied. Seven of these commented on the importance of tactical development and practicing of UGV behaviors; five remarks were positive about the UGV.

Drawbacks

The test disclosed two main perceived risks, namely that the robot may create delays in situations when timing is crucial and that it could reveal the unit to an enemy[20] (*3 and 1*). It was also considered possible that having access to a robot could make the soldiers reluctant to put themselves at risk and thereby decrease

3. Evacuation operation of combatants and civilians
4. Humanitarian assistance, catastrophe support, and evacuation of refugees
(Replies were given on a five point scale.)

[20] *Value the disadvantages the robot may convey. Estimate both the probability of the event and the consequence to the unit deploying the robot...*
1. Robot operations reveal one's own unit
2. Robot exposes operator to increased risk compared to other soldiers
3. Using the robot delays the unit during high ambition missions
4. Using the robot delays the unit during low ambition missions
5. A plan has to be changed because the robot fails
6. The availability of the robot makes the soldiers less willing to take risks and thereby decreases the capacity of the unit
(Replies were given on a five point scale.)

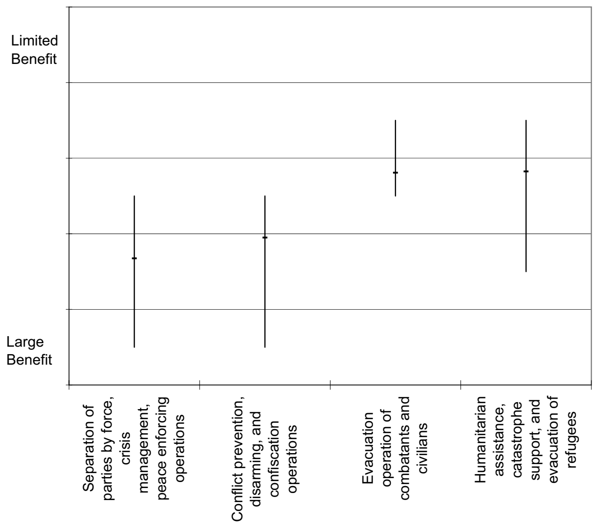

Figure 4.23. The value of the UGV in different types of operations (see footnote 19). Dots indicate the mean value and whiskers show the interquartile range.

the performance of the unit (see fig. 4.24 and 4.25). Throughout the trials the commanders generally chose not to deploy the robot if they felt a rapid action would be beneficial. However, during the interviews they stated that prioritizing tactical benefits on behalf of increased risk was probably not feasible to such an extent during real missions.

Over-all Valuation

The users' impressions of the UGV's overall costs and benefits were investigated by asking them to compare the value of the robot to two other systems also being tested by the unit: inter-squad radios[21] and night-vision goggles[22]. The robot was rated to be as valuable as the night-vision goggles, and slightly less valuable than inter-squad radios (see fig. 4.26). However, the responses were rather scattered (standard deviation of 1.3 for both). The end-users were also asked to suggest other equipment more important than a UGV. Ten responded but none of the suggestions were reported by more than two people.

A more unanimous answer was given in reply to the question of whether or not UGVs should be acquired for the Swedish Rapid Deployment Force going into

[21] *How do you evaluate the benefits of the UGV compared with the benefits of the inter-squad radio?* (Reply was given on a five point scale.)

[22] *How do you evaluate the benefits of the UGV towards the benefits of the night-vision goggles?* (Replies were given on a five-point scale.)

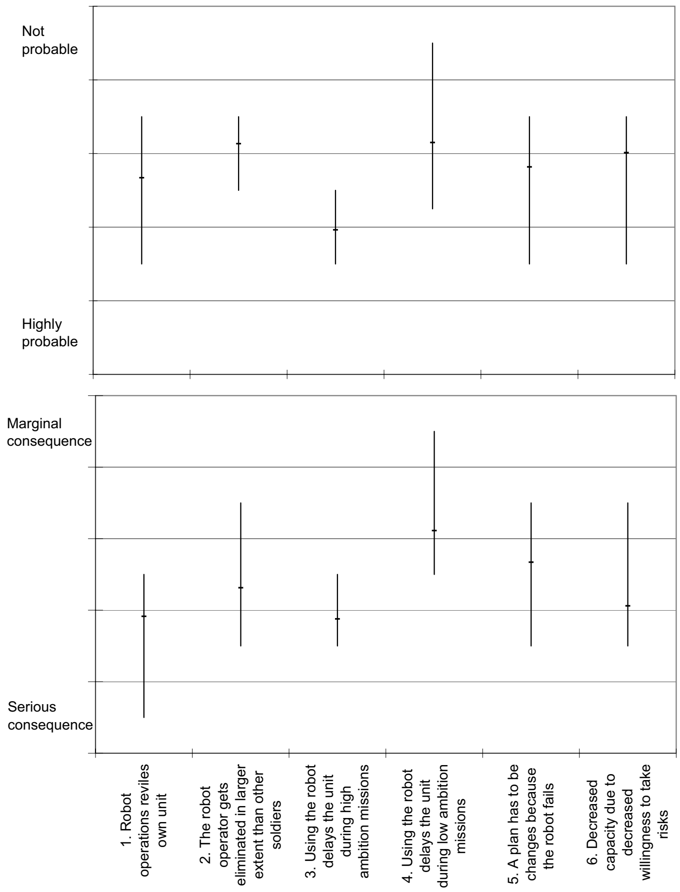

Figure 4.24. The ratings of probability and consequences given for six disadvantages of robot use (see footnote 20). A combination of probability and risk shows that the first and third were considered the most critical. The sixth alternative was also rated a serious risk. Dots indicate mean value and whiskers show the interquartile range.

Figure 4.25. The reconnaissance squad using the Packbot to *search* a residential block. The operator on the right, the squad leader in the middle and the first soldier to enter after the robot on the left. The introduction of a new feature distracted the users' general attention towards the surroundings.

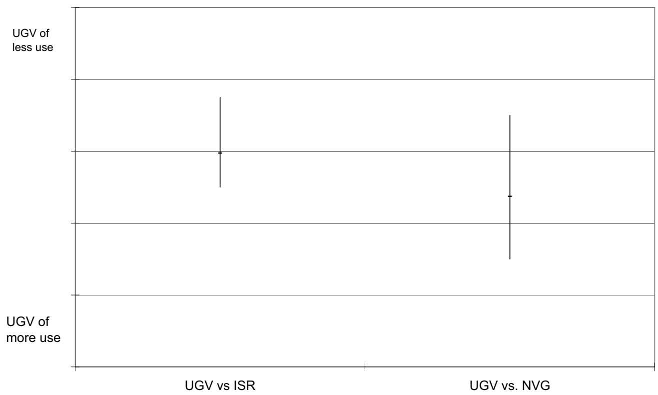

Figure 4.26. The results of the comparison of the robot with inter-squad radios and night-vision goggles (see footnotes 21 and 22). Dots indicate mean value and whiskers show the interquartile range.

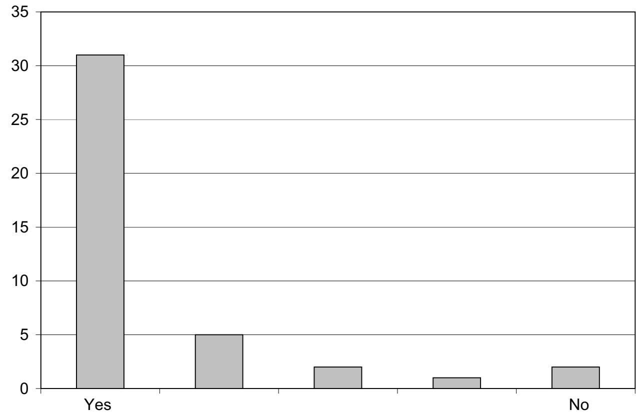

Figure 4.27. Opinions as to whether the Nordic Battle Group should be equipped with a system such as the Packbot (see footnote 23).

service in 2008 (Nordic Battle Group-08)[23]. 76% replied full support for acquisition (see fig. 4.27).

Tactical Results in Summary

After the test the users were of the opinion that a system such as the Packbot ought to be acquired for units sent on international missions. Offensive operations such as the separation of contending parties and peace enforcement were considered to be the most relevant as the UGV is of most use to units on high-ambition missions. The robot was deployed 2-10 times a day during training (which may differ significantly from real missions). The primary applications were *reconnaissance* indoors, investigation of *break-in* point and mapping. *Reconnaissance*, *mapping*, and *weapons deployment* were considered to be applications with potential once the technology has evolved. Weaponization is desired and tactically significant, but reliable identification requires improved situational awareness. The military revealed few moral considerations regarding the use of armed robots as long as there is a human in the loop of execution of the fire command. The missions were in general performed inside buildings with an uncertain enemy presence, and when time was not critical. Missions were generally short, with a specified objective in mind. Night-vision capabilities were necessary since indoor illumination cannot be guaranteed. Commanders at all levels must have a knowledge of the appropriate situations for use, time factors, and the expected quality of information in order to permit efficient use. Because of the high uncertainty during MOUT the commanders can not anticipate the need of the robot in advance. Instead, the robot

[23] *Do you think UGVs should be included in Nordic Battle Group-08...?*
(Replies were given on a five point scale.)

must be immediately accessible in order to be regarded for use. The handover of information must be swift since most of the knowledge gained with the robot is short lived. As soon as the soldiers enter the area, they will gain better situational awareness. I.e. the robot system needs to be close to the front line to allow for rapid deployment and the company therefore recommends one UGV per platoon. Deploying the Packbot in MOUT is a two-person task due to both physical and mental demands. In addition to man-portability issues, fitting the robot into the vehicles is a limiting factor. The robot is easy to spot and an enemy encounter will likely lead to loss of the robot. The robot may delay advance, reveal one's own unit and make soldiers reluctant to take risks on their own. Decreased weapons deployment and reduced risk for one's own personnel, civilians, and also enemy personnel. The ability to provide an alternative to aggressive actions such as *cleanse*. The robot was considered approximately as valuable as night-vision goggles but less valuable than inter-squad radios. Table 4.2 summarizes the main tactical findings.

Table 4.2. Tactical findings in summary

Area of concern	Main features
Opinions on procurement	Man-portable UGVs should be acquired for units heading for international operations that may include high-ambition tasks.
Primary applications	*Reconnaissance* indoors, investigation of *break-in* points, and mapping.
Ethical considerations	Weaponization of UGVs is not considered unethical as long as not autonomous.
Tactics	Robot use in MOUT is a team task. Efficient use requires all soldiers and officers of the deploying unit to have knowledge of how the system should be used. Typical missions are short and are less reliable than traditional alternatives.
Organization	One system for each platoon in order to permit rapid deployment and information sharing.
Workload	A two-person team is required for operation since controlling the robot is cognitively isolating and carrying it is strenuous.
Imposed drawbacks	Robot-use may delay advance, reveal one's own unit, and make soldiers reluctant to take risks on their own. The robot is an easy target.
Achievable benefits	Decreased weapons deployment, and reduced risk.

Technical Results

The questionnaire investigated technical issues from two perspectives: the first included technical constraints[24] , the second the value of improvements[25] . The second included both properties which were assessed during the trials and those that were not (robot armor, sensors, EOD functions, autonomy).

Narrow field of view, poor image quality, and limited radio range were considered the most limiting features (see fig. 4.28). Robot speed also stood out. The robot's top speed (3.7m/s) was, however, observed to be limiting only in open spaces or outdoors. In most indoor settings the robot was able to go faster than the speed that the operator was able to control.

Automatic mapping (during tele-operation), two-way audio, and the possibility to capture images from the video feedback for later viewing, were the highest ranked improvements (see fig. 4.29).

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[24] *To what extent do you regard the following properties as constraining the performance of the tested robot?*
1. Speed
2. Off-road ability
3. Radio range
4. Low camera position
5. Only having forward looking camera
6. Quality of video feedback
7. Power endurance
8. Physical Robustness
9. Reliability
10. Information transfer from the robot system to the persons needing the knowledge
(Replies were given on a five point scale.)

[25] *Rate the benefit of improving the robot in the following areas...:*
1. Armor against shrapnel
2. Armor against fire arms
3. IR camera detecting body heat
4. Motion detection
5. Metal detector
6. Acoustic localization of rifle fire
7. EOD indication and disruptor gun
8. Ability to manipulate and move items with gripper
9. Weapons deployment
10. Applying explosives against wall or door
11. Automatic mapping
12. Two-way audio
13. Having several OCUs within the squad
14. Improved OCU (smaller, lighter, easier to use)
15. Acquire images
16. Brighter LCD for use in bright daylight
17. Decreased latency in video feedback and steer commands
(Replies were given on a five-point scale.)

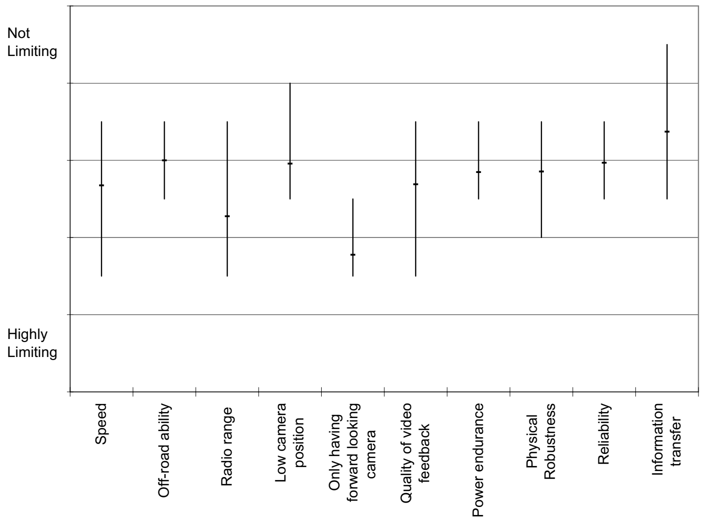

Figure 4.28. The ratings of the level of constraint the different technical features imposed on the UGV's performance (see footnote 24). Dots indicate mean value and whiskers show the interquartile range.

Robustness, Packing and Transport

Packing and ruggedness are the primary features that influence problems connected to bringing technical equipment into the field. Equipment sensitive to physical damage risks either breaking or not being used due to the negative impact on the operator's ability to act in unison with others. Ruggedness needs to correspond to other equipment in use such as radios, weapons or binoculars. The heavier or bulkier an object is, the more physical damage it has to withstand. The size and weight of the Packbot approached the acceptable limit of MOUT and any weight reduction is beneficial. That increased weight is intolerable has been verified by trials with the 30 kg URBOT (Ciccimaro *et al.*, 2003).

Adequate carrying systems are especially important for heavy equipment. The military's uniforms and carrying systems are adapted to existing gear and cannot be expected to handle new items such as a robot or OCU without modification. Packing is needed not only for the robot and the OCU, but for all system components such as chargers, spare parts and batteries. During one of the field studies, the spare batteries were found frozen in ice at the floor of a 20-foot supply container. This is not an unlikely treatment of soldiers' gear, caused by severe conditions and the pressure of time in combination with fatigue, carelessness and/or lack of knowledge. Protective cases are needed for both storing and shipping (for which size is not that important) as well as for regular deployment (which needs to suit existing vehicles).

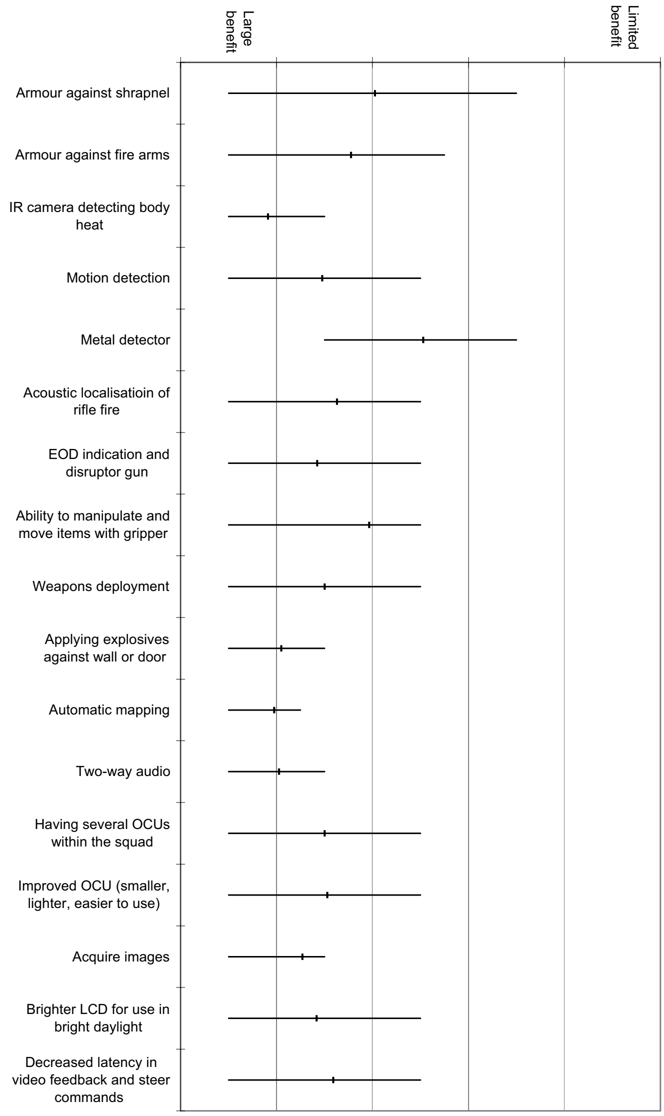

Figure 4.29. The estimated benefit of technical improvement (see footnote 25). Dots indicate mean value and whiskers show the interquartile range.

Figure 4.30. Although the Packbot is fairly sturdy it was found to have its limits. At the top a broken flipper arm, in the center holders and lid for one of the batteries and at the bottom an antenna that has come off its connector and holder after roll-over.

The Packbot Scout managed the realistic stress levels of the trials fairly well. The camera covers, antennae, and GPS receiver suffered the most damage, but connections and battery holders would also benefit from additional robustness. The *flippers* are the most sensitive part of the propulsion system and risked damage if the robot rolled down a staircase or fell from a height of over one meter (Lundberg and Christensen, 2007) (see fig. 4.30). The Packbot was never submerged in water but it withstood rain and splashes from driving through puddles. Subzero temperatures (Celsius) did not cause problems aside from decreasing the battery performance. The army is accustomed to performing their abilities, with some variance in efficiency, regardless of weather conditions, the time of day or year and so equipment needs to withstand the same conditions, or risks being viewed as inadequate. This stands in contrast to both manned and unmanned aviation within the air force, where weather limitations are tolerated.

Off-Road Ability and Audio

MOUT soldiers are almost certain to encounter obstructions such as misplaced or broken furniture or demolished buildings. A robot with an inability to traverse obstructions such as steps or stairs will limit the number of possible applications to such an extent that the system is unsuited for military applications. The environ-

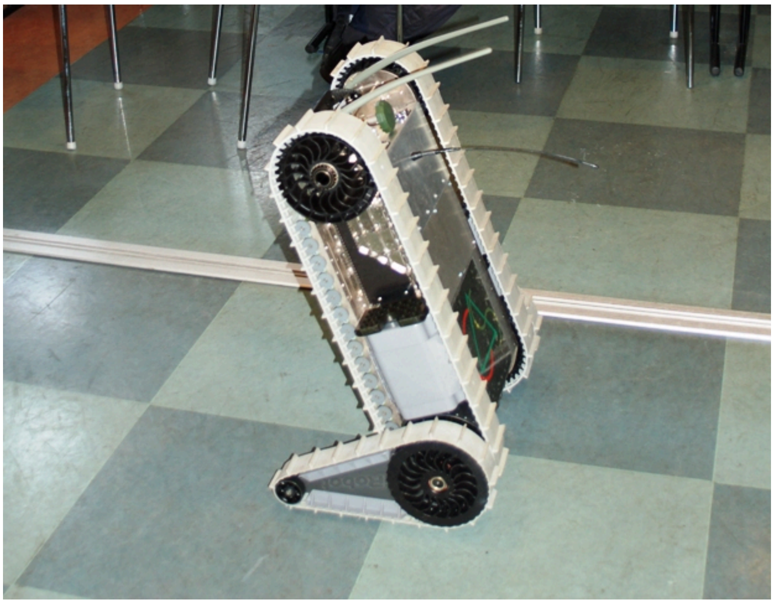

Figure 4.31. The flipper arms can be used to recover from roll-over.

ment under MOUT conditions will be more demanding than for service robotics, but not necessarily as tough as for search and rescue applications (Carlson and Murphy, 2005). During the test, ground conditions such as high grass, sand and snow challenged the skid steering of the Packbot, but only on very rare occasions did the electric motors overheat or the tracks dislocate. Snow created the worst conditions for driving, since snow gathered between the tracks and the driving wheels, which increased the track tension. In soft snow the Packbot easily got stuck because of snow piling up under its chassis. In some cases the robot could come unattached by driving with the *flippers* folded down. However, snow had generally by then piled up on the ramp in front of the camera and blocked the view. The Packbot proved unfeasible for operation in more than five centimeters of soft snow.

The *flippers*, which are a key component of the robot's terrain ability, can be used to recover from roll-overs (see fig. 4.31). They also enable the robot to pass stairs, steps and other obstacles (see fig. 4.32). Ascending stairs is easier than descending since the center of gravity in the front tends to make the robot slide when going down. Barbwire or other thin metal wire snags in the tracks and ultimately traps the Packbot. The friction in the transmission, which is normally high enough to keep the robot still while no steering commands are given, is unable to prevent the robot from moving down steep angles involuntarily. Such unintentional movement severely complicates driving in steep terrain (Lundberg and Christensen, 2007).

The soldiers, however, generally found the Packbot's capacity to pass obstacles

Figure 4.32. The Packbot ascending a staircase in one of the deserted steel factory in Fagersta. MOUT operations indoors are to wide extent carried out in complete darkness.

(McBride *et al.*, 2003) to be sufficient for the investigated application. In many cases mobility was not limited by the properties of the robot but by the operator's inability to interpret the setting through the user interface. If stuck, the robot could often be retrieved since the operator could observe the situation in line-of-sight. Noise from the robot, such as from collisions or slipping tracks, helped the operator understand the robot's situation. Multimodal feedback (visual, audio, and other such as tactile feedback of motor loads) would likely increase the operators driving performance significantly. The troops have hearing protection that electronically blocks loud noise. The headset can receive in-line audio from radios or other electronic systems and thereby permit the use of audio feedback even under noisy conditions or stealth operations. Two-way audio is a standard feature on many EOD robots which would also be of tactical value under MOUT conditions for negotiation, crowd control, rescue situations, etc. The robot was considered to be too noisy for stealth operation. In addition, booting the OCU operating system causes it to beep.

Operator Control Units

Deployment in high-risk field applications, particularly man-portable applications, implies a number of special and non-negotiable requirements. The demands on high-risk workers to be mobile and alert to sudden changes in the near environment are often as important as the ability to control the robot proficiently. Traditional displays do not meet the demands (contrast and intensity) of outdoor operation and the tough environment and handling require heavy-duty ruggedness. This implies that the OCU needs to be light-weight and portable, and that the GUI itself is carefully designed for the task at hand. Key-lock functions and power saving modes which are both efficient and allow quick access are necessary features. Integration with other systems is a critical issue in fulfilling the usability demands as the number of electronic appliances that the end-user must operate are increasing. It seems that commercially available interface platforms may not be able to meet these special requirements. OCUs must be as well adapted to the application as the robot platforms.

The Laptop Operator Control Unit

In comparison to the robot, an off-the-shelf laptop with external joystick did not suit the application so well. The weakest point of the iRobot gear was the USB connection for the joystick. It was no more rugged than that found on a common laptop computer, which became especially critical since an operating system reboot was required to regain contact with the joystick if the cable was momentarily disconnected. Both the USB port and the joystick were retrofitted with protective covers along with a carrying system allowing the operator to have his hands free for climbing, crawling, and weapon deployment. The laptop served as a basis during the trials but does not reach the top level of currently available portable or wearable technology. Major issues concern GUI design, ruggedness, portability, the daylight capacity of the LCD screen, and backlighting for the control buttons to allow identification in darkness.

The Handheld Operator Control Unit

A joystick seems to be the input device most desired by the users. Unfortunately, the design of the iPAQ joystick key has been changed to be less distinct than on previous models and is therefore not suitable for driving the robot, since forward/backward/left/right keep being pressed at the same time unintentionally. After having discovered that the joystick of the iPAQ did not work sufficiently well, the directional controls were implemented on the other hardware buttons to the left and the right of the joystick (see fig. 3.18). Although the placing of the buttons did not fit in very well with the directions they represented, the operators adjusted to using them after a while. Driving with the touch screen was found intuitive to inexperienced users but it brought the disadvantage that the view of the screen was blocked by the fingers. The touch screen also lacked tactile feedback and spatial guidance, which increased the demands for visual attention towards the OCU.

Just as for the ATRV PDA interface, the delays caused by the limited processor capacity of the iPAQ proved to be a problem. Even though the operators were able to adapt to the delays with increased experience, delays interfered severely with the systems usability, precision and efficiency. The size and weight of the iPAQ was found suitable for military use. The possibility to mount the PDA on for example the arm would permit hands-free monitoring. The shorter radio range of the PDA constituted a critical limitation. The PDA can be put in and taken out of stand by mode quickly, which permitted saving the batteries. The shorter battery life of the PDA (compared to the robot) did not cause any major problems during the tests since extra batteries, which are small and light, could easily be brought along.

The Wearable Operator Control Unit

As expected, having the OCU integrated in the combat vest proved superior to having a laptop hanging over the shoulder (see fig. 4.33). The game controller was well suited for tele-operation although it took a while to learn which buttons controlled what functions. Wiring is known to be a critical issue in a field environment. The test persons therefore appreciated the game controller being wireless and its radio link did not cause any problems during the trials.

The eye monitor has both advantages and disadvantages compared to traditional displays. It seemed to require a larger effort to switch visual attention back and fourth from the display and the surroundings, something that may improve with training. Further, it is not clear to the co-workers where the user of an eye-monitor is currently directing his attention (which is important for soldiers working together). On the positive side, eye monitors are very compact, light, and allow for hands free. Eye monitors also decrease the problem of contrast in daylight and require

Figure 4.33. Validation test of the wearable OCU.

less energy than normal displays. In addition, they emit little light and are therefore stealthy. Overlaying the most frequently accessed information on the video screen, such as is common practice in aviation, was found to be suitable (see fig. 3.20). Choosing between traditional LCDs and eye monitors for robot control is an area that calls for in-depth investigation (Blackwood *et al.*, 1997).

Power Supply

On a full set of batteries, the iRobot system could generally cover half a day's combat training[26]. Although it is standard practice to avoid the need for tools for the basic operation of military equipment, the Packbot design requires a Philips screwdriver for battery change. Replacing the laptop batteries requires a coin. Charging was carried out by the only 230 V AC source of the company, a gasoline-powered generator near the staff tent (see fig. 4.34). The generator was not run continuously, but only when time allowed the staff tent to be put up. The generator went down every once in a while, causing the Packbot battery charger to enter drain mode if the power was lost and regained with the battery inserted. Only one battery charger per robot/OCU made charging time-consuming. Lighter batteries or energy sources (instead of NiCd) would be beneficial since they constitute a large part of the system's weight. Extra robot batteries could not be brought along by the operators due to issues of weight. Attempts to keep extra batteries in the combat vehicles often failed since the vehicles tended to reposition continuously. The medical evacuation point, which should always be strategically centered and accessible to all units, proved to be a more suitable place for spare batteries and modular payloads. The advantage of having the robot and OCU run on military

[26]The OCU-laptop was delivered with one battery and a floppy disk drive. Replacing the floppy drive, which was of no use, with another battery made the laptop and robot battery times correspond better to each other.

Figure 4.34. Charging was carried out in the staff tent by a gasoline-driven generator.

standard batteries would be immense. Seven robot batteries out of twenty stopped working and two were mechanically broken during the two years of trials.

Radio Communication

The capacity and range of the radio link greatly affects the usefulness of the robot system. The practical use of the system vanishes as the video frame rate drops below ten frames per second. The WiFi link generally enabled the users to explore up to two hundred meters outdoors, and up to two rooms away inside of buildings. Unfortunately, the distance between squad members was sometimes greater than the range of the robot's radio link. This prevented the operator from moving around within the range of his group, for example in order to brief the squad leader, while maintaining contact with the robot. The circumstances for robot deployment outside differ from inside. Outside, the distance between *safe spots* are greater, which makes the limited range even more restrictive than indoors (see fig. 4.35). Other radio traffic on the 2.4 GHz frequency notably decreased the quality of the Packbot's radio link. In addition to a wider range, flexible solutions for dealing with jamming, national spectrum regulations and other radio traffic are desired. Integration with the user's ordinary radio- and command-and-control systems needs to be considered. A doubled radio range would increase the tactical performance in MOUT notably[27].

[27] It is reasonable to assume that tactical application of larger UGVs will require a significantly longer range than is required for man-portable ones.

Figure 4.35. On the left an APC, the Packbot on the right. In addition to limitation in radio range and video resolution, the terrain ability and speed of the robot compared badly with the other vehicles in use.

Sensors

Area surveillance is one of the most common military tasks and was therefore tested with the robot. Unfortunately, the current interface design made it impossible to perform in practice. To do visual surveillance using the 240*320 pixel image was simply too un-stimulating a task for a human to perform over time. Acoustic feedback would have increased the operators chance to regain attention when needed, but the obvious solution would be a motion-detection functionality. The limited resolution and field of view, in general, gave the operator a fair chance to detect human-sized targets in small rooms, such as apartments, and targets of car-size in larger rooms, such as industrial buildings. The visual feedback did not permit a reliable distinction between friends and foes (for example, by distinguishing uniforms). Increased resolution and a zoom are desirable features.

The low placed cameras were easily blocked by obstacles. The low placement also made it hard for the operator to discover negative obstacles such as a staircase approached from above or edges of balconies. This became very clear in the industrial facilities, where handrails and fences are designed for adults only and, therefore, regularly leave the space closest to the ground unprotected. Basic knowledge of the robot's design makes it easy to anticipate and avoid its field of view. With the current sensor setup, the robot is more suited to gaining spatial information rather to finding moving targets.

The poor light conditions prevailing during MOUT severely decreases SA. The IR-camera (close to the visible spectrum) was therefore the more used of the two cameras onboard. The IR-illuminator was also useful but had a range of only a

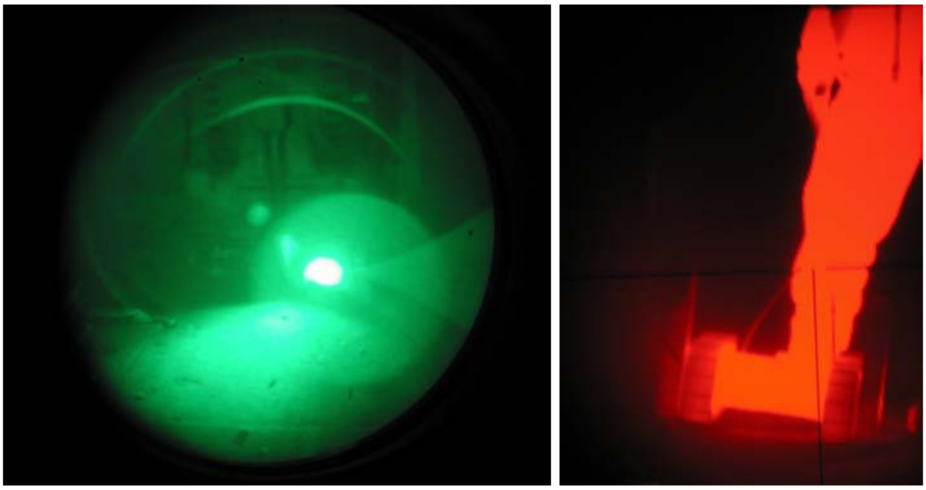

Figure 4.36. On the left the Packbot with the IR illuminator turned on, viewed through the night-vision goggles used by the soldiers. On the lower right the Packbot in front of a soldier seen through the thermal IR sight of the Bofors Missiles Robot 56 BILL. The robot has a similar thermal IR profile to that of a person.

few meters. The fish-eye camera gives a broader view which is good for passing narrows, but, unfortunately it requires normal indoor light.

Direct light, such as strong or low-angled sunlight, blinds out both onboard cameras when, for example, in a dark room facing a bright opening The IR-illuminator can to some extent compensate for glare at close range. It should be noted that the IR-illuminator, which is invisible to the human eye, can be seen through both the night-vision goggles and the night-vision mode of commercial camcorders. The Packbot has a thermal profile that is as visible as a human when observed through an IR sight[28] (see fig. 4.36). The GPS did not provide any useful data indoors or near buildings. In open terrain the range of the radio link prevented the robot from operating at a distance, thus preventing GPS-positioning from being a relevant feature.

The absolute orientation sensor and the compass may well support the operator since these parameters are hard to perceive through video feedback. Unfortunately, the iRobot GUI did not seem to bring data from the sensors to the operators' attention. A better way may be to overlay the information on the video in order to make it more accessible.

[28]Such as the one on the man-portable anti-tank missile Bofors Missiles Robot 56 BILL.

System Perspective

From the users' viewpoint, a UGV system includes more than a robot, batteries and an OCU. The military out in the field are accustomed to being provided with all the bits and pieces required along the equipment lifecycle. These include technical manuals in their native language, tactical guidelines, transport casing, special tools, spare parts, training courses, etc. Achieving this will require joint efforts from industry, third part developers and users.

The successful integration of UGVs in the armed forces requires consideration of a broad range of issues, such as the power supply, radio communication and maintenance together with command-and-control. The special needs of robot systems, for example, bandwidth for real time video, will have to be enforced well in advance in order to be implemented in the military hardware structure. The ongoing process of equipping each soldier with a portable computer, sensors and radio has to be considered when designing future OCUs. In addition to adapting to future technology it should be considered that the turnover time for equipment in organizations such as the military is long, which makes compatibility with older systems an important issue. It should also be considered that high-risk work groups spend a lot of time on training (the military in general spend more time training than carrying out real missions). The military have both rules and technical systems to evaluate damage and losses during exercises. A robot system included in training must be implemented in the evaluation system. Further, a fair amount of integration will be necessary in order just to achieve relevant testing during research and development (see fig. 4.37). A wide range of standards must be complied with. Some examples are: Environment – *MIL-STD 810*, System Safety – *MIL-STD 882*, Human Factors – *MIL-STD 1472F*, Certification for Deployment in Explosive Atmospheres – *ATEX Directive 94/9/EC*, Non-magnetism – *Stanag 2897 Annex C*[29], and Electromagnetic Interference – *MIL-STD 461/462*.

Technical Results in Summary

The size, weight, mobility, robustness, and endurance of the robot live up to demands. The OCU needs to be reduced in size and weight to fit the application and its ruggedness and usability should be improved as well. Increased visual feedback, longer radio range, and two-way audio are the most desirable improvements. GUI features such as snap-shot and automatic mapping would be valuable features.

Operation outdoors is restricted by the radio range, robot speed, off-road ability, camera resolution and glare. The robot operates more efficiently indoors. Gearbox noise restricts advance by stealth. Integration with other military equipment such as radios, command-and-control systems, and energy supplies will greatly influence future overall performance. Table 4.3 further summarizes the main technical findings.

[29]Non-magnetism is a requirement for EOD tools.

Figure 4.37. A platoon commander carrying no less than three radio systems during tests with inter-squad radios. System integration must be considered not only for the final product but also to permit relevant testing. In this case the operator was heavily loaded with just wearing and maintaining the radios.

Table 4.3. Technical findings in summary

Area of concern	Main features
Requirements fulfilled	Size, weight, and robustness, of the robot live up to demands. Mobility and speed are sufficient for indoors operation. The power endurance of the system is adequate.
Limitations and desired improvements	Narrow field of view, poor image quality, and limited radio range constitute the main limitations. Operation outdoors is in addition prevented by mobility and speed. The night-vision capability proved to be very valuable, but, its range needs to be improved. There was no purpose for the GPS. Noise was the most revealing factor. The robot has an IR-profile comparable to that of a person. The OCU needs adaptation for portable field use. Automatic mapping, two-way audio and facility to capture images are desirable features. Making use of standard military components such as batteries would simplify the handling and maintenance of the robot. There are a number of procedural, environmental and military standards to be complied with.

Chapter 5

Results II – SWAT

This chapter presents the results from deployment of the Packbot and the distraction siren payload by the SWAT police. First, the characteristics and tasks of SWAT work are described, followed by the experiences gained from robot deployment.

5.1 User Characteristics

Organization, Demography, and Training

Sweden has three main SWAT units: Malmö, Gothenburg, and Stockholm, which attempt to keep methodology and gear aligned since they occasionally carry out joint missions. The Stockholm unit, 85 members strong and the largest of the three, is organized into eight SWAT teams, each consisting of 8-9 officers. Each team works four shifts per week. The number of teams in service varies with the expected amount of crime, with at least one team on duty at any given time. During the daytime it is common to have one team on duty, and another scheduled for training and acting as backup. Although the teams have an appointed leader, most decisions are made jointly. Hierarchical leadership is enforced only under pressure of time. The Stockholm SWAT unit has four mission commanders who handle scene-of-crime command and communication with the police chief. 22 negotiators are associated with the SWAT unit. Most of them are stationed elsewhere but are on call. Due to physical demands, the members of the SWAT teams are currently all male[1]. Negotiators on the other hand always work in a pair of one male and one female and it is attempted to have a diverse ethnical background for reasons of tactical advantage.

The average age within the SWAT team is 36 years. Average time spent with the unit is 8-9 years. A minimum of five years of police service is required before being considered for the 3-month special SWAT training. 20% of working hours are spent on training, which is handled to a large extent within the teams. In order

[1] A program to equalize the gender distribution is on-going.

to act swiftly and in a synchronized manner, the SWAT teams use predefined and well-practiced concepts based on reference scenarios. This is the case although the SWAT police consider themselves to be less oriented towards predefined behaviors than the military. I.e. the police allow individual solutions from one case to another to greater extent. Despite all teams receiving the same basic training and having the same gear, they occasionally develop their own behavior depending on experiences encountered Individualization above team level is discouraged by management in the interest of interoperability. In the past all SWAT team members were encouraged to handle all techniques and equipment. The recent increase in technical complexity has required the team members to assume specialized roles. Maintaining competence for different technical aids at a high level is considered a problem and new gear is not always properly evaluated.

Tasks

In contrast to many other police units, whose objective is more oriented to preventing crime, the SWAT teams are mainly reactive, although they are occasionally deployed proactively to demonstrate that they have the suspects under observation and are ready to strike. Their main objective is to target dangerous situations. Common tasks include resolving hostage situations, arresting potentially aggressive suspects, and taking suicidal or violent mentally disturbed persons into custody. In other cases they are called upon to carry out rapid arrests or searches to prevent suspects from disposing of evidence. The SWAT teams may also be used for riot control or routine missions such as high-risk escorts or searching for missing persons.

Missions are initiated either following notification of an on-going crime, or after a request for assistance from another unit (response or planned missions). Responding to an on-going crime is more frequent. Apartments or houses are the most frequently targeted environments, but *open-air* missions occur as well. The SWAT units are equipped and trained to carry out their duties wearing gas masks. Targeting suspects in possibly toxic environments occurs 2-4 times per year[2]. The Stockholm SWAT unit carries out on average close to one high-risk mission per day. A total of 600 missions were carried out during 2006. Of these, half were classified as high-risk. The most common tasks include dealing with previously convicted suspects or organized crime.

Typical Scenario

In advance of planned missions, the appointed units usually survey the target in detail[3]. This includes gathering evidence, getting to know the suspects, what weapons

[2]The Swedish Emergency Management Agency is funding acquisition of sealed CBRN vehicles to provide the police with the capability to operate in hazardous environments in which robots could play a role.

[3]This was also reported by Jones *et al.* (Jones *et al.*, 2002).

and vehicles they have, and the layout of the strike scene. If the suspects reside at different addresses, the arrests are often synchronized. Planned missions usually occur before or after the crimes are committed, in order to minimize risk to third parties.

During crime response missions, the first objective is to locate and confine the suspects to prevent escape or hostage taking. Subsequently, the mission commander, the SWAT team commander and the negotiators decide how to address the situation.

A defensive approach, which entails the suspect surrendering according to conditions stated by the police, is preferred. Negotiation makes up a large proportion of this situation and can be a tedious process[4]. Long negotiations challenge the SWAT teams' ability to maintain a high level of readiness. Missions lasting longer than 6-9 hours require a relief unit.

Offensive actions are based on forceful confrontation with the aim of shocking and overwhelming the suspects. Distractions such as tear gas, pepper spray or shock grenades may be used. The use of distractions or the deliberate firing of weapons (for purposes other than self-defense) has to be sanctioned by the police commander.

The Swedish police are increasing efforts towards non-violent solutions through negotiation[5]. Reducing violence against humans is regarded as far more important as avoiding material damage. Breaking down doors is the most common form of destruction during SWAT missions.

Limitations

When asked about the main limiting factor, the robot operators responded that the restrictions imposed by the commanders[6] were the most constraining on their performance. Despite proper competence, knowledge and the tools to act, the SWAT teams feel they are held back from solving cases.

Personal risk was not reported to be a very limiting factor, and mission commanders usually take preventive measures to avoid risks to third parties or the suspects long before the SWAT officers believe themselves to be endangered. The most life-threatening moments were considered to occur during emergency vehicle journeys or vehicular pursuit. The SWAT officers argued that their being aware prepares them for dangers, whereas the police generally encounter high risks to a greater extent by surprise. They also reported that they are often able to demonstrate enough superiority to cause the suspects to surrender without resistance.

[4] On one occasion negotiations lasted for 44 hours.

[5] The intention to achieve non-violent solutions has been shown to vary greatly between countries. In particular, Australia and United Kingdom were mentioned to favor negotiation before force.

[6] Police chief as well as the mission commander.

5.2 Robot Deployment

Once the team had familiarized themselves with the robot, they decided to include it on missions involving five or more police officers. This was the case on about half of all missions carried out. On missions with fewer than five participants, the team generally considered that no one could be spared to operate the robot. In addition, the jeep used to convey a small number of people did not have much extra space and accommodating the robot was not a problem for large teams since they had access to a van. Since only one SWAT team was trained to take the robot, and did so on half of their missions, the robot was available roughly 10% of the total time.

The robot was deployed on one real mission during its five-month trial[7]: it was used to investigate a suspected bomb on a staircase outside an apartment. The suspected bomb was located outside an apartment used for persons under protection. The robot enabled the police to keep the suspicious object, as well as the surroundings, under observation without having to approach it themselves. Once the bomb squad arrived, the robot was used to gain initial information about the object and the surroundings. While the object was targeted by a bomb-technician wearing a bomb suit, the robot was used by the others to monitor progress.

The robot was also considered for the exploration of a smoke-filled shop which was not on fire. After the team broke down the door of the shop, they intended to use the robot to search for victims, but the fire brigade arrived and took over before the robot mission was begun.

The operators reported that it is usually possible to find a *safe spot* for the operator. Handling the robot was not found too challenging for field operation, though the control unit lacks key-backlight which is required in darkness. The operators considered the video feedback to be fairly adequate. However, they thought an improvement in resolution would be beneficial, as well as the ability to pan/tilt the camera, since having to elevate the front of the robot with the flippers to view upwards proved time-consuming. A rear-facing camera was suggested to make backing out of narrow spaces more convenient. A zoom function was further suggested to permit closer inspection[8].

The range of the radio link was considered sufficient to cover apartments, which is the type of building targeted the most. Operations were usually carried out from a staircase or neighboring apartment. Ruggedness and reliability were satisfactory as well, although the users claimed the OCU and the robot sometimes failed to synchronize[9].

Spiral staircases were the only obstacles said to pose a problem. This problem became evident during the real mission targeting the suspected bomb. Police vehi-

[7] Until 18 February 2007

[8] A rear-facing camera and zoom are features available on the URBOT (SPAWAR, 2007a).

[9] This error may have been caused by the fact that the OCU does not work properly after having been put in, and taken out of, the laptop's standby mode. The standby mode is activated by hitting the on-button while the ESC key is used to turn off the laptop. Making the mistake of attempting a reboot using the on-button may have been the cause of the *robot comms lost* error.

Figure 5.1. Tactical test of the distraction-siren. From left to right: the officer acting as criminal; the officer acting as hostage; the two SWAT officers attacking. The hostage taker was instructed to shoot at the police, which he succeeded in doing despite the siren. The hostage immediately plugged his ears with his fingers. The electronically filtered hearing protection used by the police protected them from the noise.

cles can generally approach the mission area at fairly close hand, thus ensuing that the distance the robot has to be carried is not very far. The robot was considered heavy although not a major obstacle. Size became a problem only during vehicle transportation.

The users immediately noticed the absence of two-way audio, which would make voice communication possible with suspects and victims. Missions including negotiations may, as mentioned, last for an extended period of time. Battery replacement and the facility to charge batteries, both from wall sockets and vehicles, are needed. The operators additionally suggested the ability to charge the batteries while mounted in the robot, instead of first having to remove them.

The test showed that the noise from the siren, although extremely annoying, does not completely disrupt will-power (see fig. 5.1) Yet the siren was considered useful as it is less violent compared to shock grenades or chemical agents, and therefore may be less restricted in use. Suspects' and victims' reaction to the robot is an open issue since the robot may appear frightening, increase aggressiveness or be ignored. The trials did not give any opportunity to investigate this issue, which can hardly be examined with validity during training.

Considerations on Future Deployment

Apart from the mission actually carried out (inspection), the respondents indicated a number of possible applications. The most prominent task suggested was to use the robot as a tool during negotiation. In the first phase it could be used to establish communication with the suspect either by bringing in a cell phone/radio or establishing a two-way audio link through the robot. During negotiation, the robot could be used to transport items to and from the suspect (the suspects often demand food, cigarettes, etc.). The robot could furthermore be used for retrieving weapons in the event of surrender.

Using the robot for the mentioned applications would provide the opportunity to observe the suspects' aggressiveness, rationality, arms, the premises and possible any hostages. If negotiating with suicidal individuals, the robot may be used to monitor their behavior. As demonstrated on the real mission, the robot can also be used for the visual inspection. A robot equipped with non-lethal weapons could be used for distraction if negotiations fail. Adding non-lethal weapons such as tear gas to the robot, however, poses a risk, as the weapons could come into the offenders' possession. It was suggested that the robot should have a self-defense system, such as electric shocks.

Another suggestion was to use the robot for the long-term surveillance of a door or a passage in order to relieve police officers. The robot could also enable the police to manifest their presence without exposing personnel to risks. Additionally, the robot could be used for missions in hazardous environments if equipped with the appropriate sensors. The operators stated that the robot would mainly be used for defensive purposes on missions, i.e. to locate suspects and initiate negotiations, rather than to target them. The robot was not considered suited for offensive deployment as it does not have the ability to act against the suspects and because it is too slow. To circulate and map an area holding the suspect did not seem to be a possible application. It was pointed out that outdoor operations could be useful, although this was not tested to any greater extent. Considering the restrictions for using violence, the operators did not regard equipping the robot with lethal capabilities to be of any interest.

The main benefits robots could bring to SWAT deployment were as an enabler of a number of new features during negotiation, and also some new tactical advantages if the mission had to be solved offensively. The users did not expect the system to have a major influence on their personal risk. The police did not consider the robot to have imposed any major disadvantages. The only negative issue mentioned was that a robot system would entail yet another high-tech utility requiring maintenance, training, transport, etc. It was not believed that the option of a robot would make the police officers decline to carry out hazardous duties themselves. In addition, it was mentioned that an action-oriented mindset and firm intention to achieve immediate results may prevent the SWAT police from deploying the robot.

Acquisition

The operators were asked to estimate how often the robot would be deployed if the suggested improvements were included. They felt that their team had encountered unusually few opportunities to deploy the robot during the evaluation period, but one of the operators estimated that the robot could be part of every fifth high-risk mission of the Stockholm SWAT unit (about once per week).

One of the two operators unanimously argued that the tested system should be acquired once two-way audio and key-backlight had been incorporated. The other operator was in two minds. Although he stated that the robot could be valuable, he argued that acquisition would depend on cost and estimated the price limit to be about USD 29,000. The other operator estimated the price limit at about USD 43,000-57,000. These amounts correspond fairly well with the tolerable price limit of USD 20,000-30,000 (year 2003) as reported by Ciccimaro *et al.* (Ciccimaro *et al.*, 2003).

Neither of the operators could suggest any alternative equipment they currently lack that would be preferred over the robot. On the other hand, they did indicate occasional shortage of personnel to be a limiting and risk-increasing factor. When asked to compare the benefits of the robot to night-vision goggles, both operators argued that night-vision goggles would be more useful.

Both respondents agreed that one robot would fulfill the tactical needs of the entire unit. Having a second system for training and for backup would be convenient. The Stockholm unit has just been equipped with a designated vehicle for the new technical equipment. It was suggested that the robot should be stationed in the tech vehicle. Estimating how many robots would be destroyed during a year proved difficult as the suspects' reactions to robot encounter had still not been experienced. One operator argued that it would probably be few while the other chose not to speculate.

Chapter 6

Comparison and Discussion

This chapter starts with providing the findings from the surveys carried out on the firefighters, CBRN and EOD teams as a basis for discussion. Next a structured comparison of robot requirements within all five user-groups is given to identify the extent to which they could deploy the same type of robot. Then the approach taken for research, as well as the results in general, are discussed. The viewpoints are presented according to topics rather than separated according to the phases or user groups they originate from.

6.1 Comparison

Firefighting

There are many ways in which firefighters can benefit from robots (Hisanori, 2002). One of these, handling gas cylinders, is practiced at the Södertörn fire station, Stockholm. Acetylene[1] cylinders are the most dangerous since heat can induce a chemical reaction which is unpredictable over time and may lead to explosion. Acetylene becomes highly unstable when compressed, and is, therefore, dissolved in acetone which is contained in a porous filling that enables storing and transport in steel containers. Acetylene tubes that have been exposed to heat either have to cool for a minimum of 24 hours or be punctured so that the gas and acetone can be burnt in a controlled fashion. The puncturing and incineration are executed by firing repeated tracer rounds[2] with a sniper's rifle from a safe distance (Lamnevik, 1996). The robot is used to localize and make tanks accessible for rifle fire.

Attempts to neutralize acetylene tanks are usually made once a fire is under control or has been extinguished. Often the existence and location of hazardous

[1] C_2H_2

[2] Special bullets with a small pyrotechnic charge in their base which ignite upon firing and make the projectile visible to the naked eye. This enables the military (who are the original users of this type of ammunition) to follow the bullet trajectory relative to the target in order to make corrections to their aim. In this application the purpose is to ignite the gas.

objects can be investigated by questioning persons acquainted with the area or by studying the nature of the building, e.g. workshops, constructions sights, etc. If possible the acetylene tanks are targeted in their original position. The procedure requires a minimum firing distance of approximately 100 meters[3] and the sector behind to be solid enough to stop a bullet. The robot is used to localize tanks, to clear the way to permit rifle fire, or to move the tank to a suitable position.

Approximately 20-25 situations including acetylene occur per year in the Stockholm area and about half of these could be dealt with using a well-functioning robot. Unfortunately, the current system only meets the demands for about three missions per year. The poor reach and quality of the video system restricts the robot's overall performance the most. The images flicker even at close range and the practical range of operation is only about 100 meters. Using the gripper is challenging, as mono-vision makes it hard to determine the distance to the object. To compensate, one of the operators had come up with the idea of mounting a drinking straw on the gripper as a tentacle for depth estimation. Access to residential and office buildings is hindered by the robot's size. The firefighters working with the robot found that colleagues from other stations were sometimes skeptical about the robot as they did not see it in use very often. In general, fire brigade acquisition is characterized by high demands for robustness, reliability, usability and frequency of deployment. The prospects of maintenance and technical support in the long-term are other important issues. The fire department is generally less accustomed to funding studies or technical development compared to e.g. the military. However, the Södertörn fire station has recently put together a work-group to specify requirements and to investigate the possibility of replacing the current system. The main benefit of robots in this application is to reduce the time that an area has to be isolated due to the risk of explosion.

CBRN Contamination Control

CBRN contamination control is a task which, fortunately, does not have to be carried out very often in modern conflicts (compared to e.g. EOD). It is, however, a capability considered indispensable amongst modern armed forces. CBRN detection is not only a military matter. The police, first responders, border control, emergency response, nuclear energy production and the chemical industry must also be able to carry out reliable, safe and efficient detection.

The Light-role CBRN team (which was the unit investigated, see 3.6) consists of two lieutenants, a nurse and five soldiers. The team can be self-sufficient in terms of transport, communication and supplies for a few days. The team can be allocated to any unit within a battalion.

Most CBRN missions target hazards which have been previously detected by others. This implies that the CBRN team will be provided with information such as

[3]The ignition of the tracer round's pyrotechnic charge is delayed about 70 meters in order not to reveal to the enemy the position of the shooter.

weather conditions, location and suspected type of contamination before arriving. The first measure upon arrival is to establish a *Clean Dirty Line* which defines where it is safe to be present without protective gear. Later the *Clean Dirty Line* is used to keep track of contaminated gear. Next, members of the marking team are suited up, which takes approximately half an hour. Working in the suit is tiring and work shifts are therefore limited to an hour at the time. Further, the protective gear restricts rapid movement, climbing, crawling, and passing narrow gaps or operating near objects that may damage the suit. In the event of risk of an encounter with the enemy additional soldiers must be suited up to handle close-range defense. Entering a contaminated area that may convey a hostile encounter is, however, avoided. Tactical CBRN missions are mainly carried out to avoid or escape exposure. Initial reconnaissance and marking are carried out using a number of sensors and after completion the necessary instruments are once again taken to the identified sources to carry out more precise measurements, gather samples for evidence, etc. Communication is carried out by radio. Mission time is mostly not critical but may be constrained by the tactical requirements of other units, or when dealing with a rescue situation. In other scenarios, such as investigating violation of international law, time is of secondary importance. In either case the completion of a CBRN mission is a matter of hours.

Of the possible CBRN hazards, radioactive ones are detected with the greatest reliability. Chemical agents are often traced through an element forming part of the compound, for example sulfur in mustard gas. The presence of the indicated element in other non-hazardous compounds, such as sulfur in diesel fumes, may lead to erroneous indication. Biological agents, such as bacteria or viruses, are the hardest to accurately detect in a field setting.

CBRN indication can be divided into two categories depending on how close the sensor must be to the investigated specimen. Hazards which can be detected by a sensor at a range of several meters, such as gamma radiation, gas agents, low oxygen level, explosive gas or smoke, may be investigated by a robot with sensors mounted on the chassis. Other substances, such as alfa and beta radiation, chemical agents in a solid or liquid state, biological agents or explosives, require the sensor to be in contact with the substance or within close range, which requires having the sensor mounted on a robot arm.

Apart from doing detection, marking, and sample gathering, robots can be used to investigate the layout of premises, to visually detect any presence or spillage of industrial or medical toxins, and to search for persons (enemies, civilians or wounded) in advance of entering. A secondary application of the robot would be to use the robot to transport samples and gear between the *Clean Dirty Line* and personnel working in the contaminated zone.

CBRN equipment is generally fairly expensive and acquired in small amounts for specialized teams rather than for every unit. The costs of robots may, in comparison, not be a crucial issue once it has been shown that it is of significant value. The greatest advantages of a sensor-equipped robot are probably the enabling of immediate action upon arrival, increased endurance, thus reducing exposure to personnel by using the robot for early *reconnaissance* and detection before deploying personnel.

Explosive Ordnance Disposal

The EOD task can be divided into the sub-categories of mine clearing, handling unexploded ammunition, and dealing with IEDs, tasks that have to be performed both in the armed forces and civil society. The Swedish military and police disposal of explosives is highly coordinated. This includes using similar gear, full information-sharing, combined training, and carrying out joint missions (national).

The clearing of a suspected explosive is typically initiated with an interview of the individual who reported the object. In a civilian setting, the hazardous area is sealed off, which may be of secondary importance in military applications, where it instead may be necessary to establish a close-range defense against enemy forces to protect the EOD team. The area of hazard varies greatly depending on the type of explosive, infrastructure and terrain[4].

The Swedish military and police ordnance teams consist of four persons and two all terrain vehicles. They carry gear for both manned as well as unmanned intervention by default, and the primary mode of operation involves use of the robot, which is possible in about 60% of the cases. If the robot fails, one of the ordnance team members is equipped with a bomb suit (see fig. 6.1) to either solve the problem hindering the robot, for example by opening a door, or to finish the mission manually. Working in a bomb suit, which weighs 35 kg, is physically demanding and can only be carried out for about 45 minutes at a time and, due to the danger, there is additionally significant mental stress. The police bomb squad in Stockholm carries out approximately 130 missions per year, and only about 10 of these include real explosives. The military were, for reasons of security, unable to go into detail about deployment frequency.

The war-time approach to neutralization is to large extent based on destroying hazardous objects on site by water disruptors[5], and by destruction or detonation using explosives. Repeated firing may be necessary and the weapons can also be used to breach obstacles such as doors. The prime tactical objective for an EOD mission is often to eliminate the threat as quickly as possible in order to clear the way for other troops. Civilian missions may be constrained in time by commercial interests, e.g. reopening an airport, or demands to move or defuse time bombs before detonation.

Under circumstances where infrastructure has to be protected, an attempt is usually made to move the hazards to an open and isolated area or a bomb lab for neutralization. Blast-safe containers are used for transport. Insertion into and removal of objects from the transport containers is often a challenging task for

[4]Security regulations prevented the respondents from going into detail.

[5]A disruptor is used to mechanically destroy IEDs by shooting at them. There are several types of disruptors, water-jet, shotgun, and needle. Sniper arms can be used from a distance for the same purpose.

Figure 6.1. Working in a bomb suit, which weights 35 kg, is physically demanding and can only be endured for about 45 minutes. Dressing up takes about 15 minutes.

a robot. A bomb lab is a blast-safe building with a robotic arm which permits the dismantling of IEDs in order to examine the design and to gather evidence. This is of special interest to the police in order to secure evidence. Portable X-ray systems are valuable tools for the investigation of suspicious objects; they weigh about 15 kg and can be placed in the vicinity of the object of interest using the robot. The military, in general, have to be prepared to deal with heavier objects such as unexploded artillery shells while the IEDs encountered by the police are most often the size of a briefcase. Traditional EOD robots, such as the Andros, are too large to enter narrow areas such as airplanes or ships. They are also too large for houses, apartments or basements which are often where bomb makers do their assembling. This is an issue that used to be a challenge for the police but which is becoming increasingly significant also for the military since the use of IEDs is increasing (iCasuaties.org, 2007). Within the group of instructors it was believed that a smaller robot would be able to solve 80% of all the missions while a larger robot, such as the Andros used today, can manage 60%[6].

There is a risk that the operator may get lost while working with the robot in large and complex buildings. Operating the robot arm is, however, the most

[6]These estimations were based on experience rather than a quantitative investigation.

Figure 6.2. The arm of the Remotec Andros EOD robot. To the right of the gripper there are two water disruptor guns. Cable ties are taped onto the front of the disruptors to help the operator to judge the distance from the muzzle to the object. Reaching into a window of a car is a challenging task and collisions are common.

challenging part of operation. A common task is for example to reach in through a car window, which causes problems as the cameras observing the arm get blocked or do not cover the entire arm across all positions. In other cases the operator fails to correctly assimilate the information provided by the different cameras. Arm collisions are not uncommon even for experienced operators, and may lead to damage to the arm or the payloads mounted on it (for example water disruptors). While grasping objects, the operator uses shadows from the gripper to evaluate its position in relation to the object (see fig. 6.2). Estimating the gripper's position is challenging. Shadows create helpful references and lights are therefore used even in daylight.

The greatest benefit of EOD robots is to reduce the risk to personnel. The major limitations were stated to be the range of the wireless communication link, the top speed of the robot, terrain traversability, the size of the robot, and the tether (if deployed). The robot is considered to be a very valuable and expensive asset which should not be exposed to unnecessary risk. Each team has only one robot and replacement may take some time, during which all missions would have to be carried out manually. The Defender (see fig. 2.9) is about USD 350,000 in its basic configuration, to which another 25% approximately needs to be added for accessories and modifications.

Priorities within the Five Groups

As a base for comparison the five groups were evaluated according to 20 criteria, see table 6.1. The importance of the criteria to the different users was rated on a scale from *1* to *3* depending on the importance of the different applications. The priority rating does not give an absolute rating, but rather ranks the relationship of the need for the criteria in-between the groups. A *1* indicates the criterion to be crucial, a *2* to be of value, and a *3* to be of marginal or no value.

The justifications for the priorities in table 6.1 are:

1. Access housing & offices: MOUT, SWAT, EOD and CBRN teams all need to be able to access premises such as offices and housing. The targets of firefighters are most often found in less confined areas such as industrial facilities, workshops and construction sights.
2. Off-road performance: Obstacles such as steps and stairs are common in most buildings. During high-risk missions it is also likely that infrastructure have been destroyed, which entails additional obstructions. A robot unable to traverse common obstacles such as steps will be crucially limited as to the number of possible missions. MOUT troops moving on foot are highly mobile, which is required both for covering ground and to avoid exposure to the enemy. In principle, SWAT teams operate in the same type of area, but are likely to encounter less destruction and therefore make smaller demands on off-road capabilities. The other three groups are accustomed to being restricted by protective suits, gas masks, etc. User groups who themselves experience limitations as to terrain ability are more inclined to tolerate the same "deficiency" in robots.
3. Man-portability: MOUT troops require man-portable gear as many of the operations include leaving the vehicles behind. The other groups are usually called out to address a specific target which can normally be approached with vehicles within a couple of hundred meters[7]. It should be noted that portability demands include both the robot as well as the user interface devices.
4. Power endurance: EOD, CBRN and firefighting missions[8] are typically carried out at a slow pace in order to ensure precision and control, which requires the robots to have a power endurance of several hours. Time is normally allowed for recovery and

[7]The Swedish EOD teams have recently initiated an investigation of compact EOD robots in order to access premises too narrow for traditional EOD robots (Swedish Defence Material Administration, 2007). The high number of EOD robots being deployed in Iraq indicates that EOD robots that are easy to transport and that can be put into action quickly are advantageous.

[8]When targeting acetylene cylinders.

Table 6.1. The 20 criteria are in rows and the five user groups in columns. A *1* indicate the criterion to be crucial, a *2* to be of value, and a *3* to be of marginal or no value.

		MOUT	SWAT	EOD	CBRN	FF
1	**Access housing & offices**	**1**	**1**	**1**	**1**	2
2	Off-road performance	1	2	2	2	2
3	**Man-portability**	**1**	2	2	2	3
4	Power endurance	2	1	1	1	1
5	Robot speed	1	2	2	2	2
6	Ruggedness	1	2	2	2	2
7	Night vision	1	1	2	2	2
8	Stealth	1	2	3	3	3
9	Transport and drop	1	1	1	2	3
10	Light manipulation	2	3	1	1	1
11	**Medium manipulation**	3	3	**1**	3	**1**
12	**Heavy manipulation**	3	3	2	3	**1**
13	Multi-role capability	1	1	2	1	2
14	Radio range	1	2	1	1	2
15	Usability demands	1	2	2	2	2
16	Reliability	1	1	2	2	2
17	Development of robot work procedure	1	1	2	1	2
18	Compliance with standards & other systems	1	2	1	1	2
19	Mass production	1	2	2	2	2
20	Price sensitivity	1	1	2	2	1

recharging batteries after each mission. The task of long-time surveillance within SWAT missions calls for long endurance. The MOUT missions carried out during trials were typically short but intense, ranging from a few of minutes to half an hour. However, it has to be kept in mind that MOUT troops normally carry out repeated missions before being able to replace or recharge batteries. Both the Defender (see fig. 2.9) and the Packbot have a power endurance of several hours.

5. Robot speed: MOUT soldiers are able to advance significantly faster than a robot. Rapid movements are often of tactical interest in order to quickly move past exposed passages or to surprise the enemy. The missions suggested by the SWAT police (negotiations, transport, surveillance) do not require the robot to move exceptionally fast (the speed of the Packbot was considered sufficient). For the other groups the robot speed is mainly of importance for the overall mission time which, in turn, may have a tactical effect on a higher level or influence costs to society. Although the EOD personnel have pointed out the robot's speed as being restrictive (frustrating), moving the platform does not normally constitute a major part of the total mission time.
6. Ruggedness: EOD, CBRN and firefighting personnel have a high technical understanding and are used to taking into account and adapting to technical limitations – both for equipment in general and for robots. MOUT and SWAT gear has to stand up to much abuse since the demands for high mobility and swift action make it hard to handle gear with care. It should be noted that the heavier or bulkier an item, the more abuse it will have to withstand.
7. Night vision: All of the investigated applications are likely to encounter dark premises. MOUT may in addition need to avoid white light illumination in order to escape enemy detection.
8. Stealth: The ability to advance quietly is important in MOUT as stealth behaviors are a fundamental tactic. Thermal signature (infrared) is also an issue during MOUT tasks such as combat *reconnaissance* since thermo-optical devices are used for enemy localization. The thermal signature of a MOUT robot should, therefore, not exceed that of a person. If available, a stealthy robot may also be used for SWAT missions.
9. Transport and drop: Transporting and dropping objects (the object does not always have to be positioned very accurately), is a fairly simple task which can be very useful. Transport and drop is carried out within EOD where explosives are placed on the hazardous objects which are then blown up (once the robot has left). Another EOD application is the investigation of suspicious

objects with a portable X-ray device (which could be placed in position either by hand or by means of a robot). The mentioned tasks are today solved with EOD robots which have rather sophisticated arms, but simpler, lighter and less fragile technical solutions could fulfill the need. The ability to place loads against walls or doors would be a valuable feature in MOUT tactics. Transport and drop will probably start off as a tactical feature (rather than for logistics) and a capacity to handle objects of up to 10 kg would cover many applications.

10, 11, 12. Light (<5kg), medium (<20kg) and heavy (<70kg) manipulation[9]: The ability to physically interact with objects is key to both EOD and firefighting missions, even though the weight to be handled ranges from a few to 70 kg. An arm, possibly equipped with sensors, could also be a valuable feature in CBRN work (Gardner *et al.*, 2006), although this is not a requisite for initial robot deployment since sensors which do not require close contact are a likely initial step (Smith-Detection, 2007; Foster-Miller, 2007a). There is significant potential for improvement to the tele-operated arm control in use today. Arm collision avoidance, depth estimation, and support for grasping are highly relevant features. EOD missions sometimes require rather complex manipulation or the need to carry out parallel manipulation, i.e. manipulation with more than one robot arm. A secondary arm, which may well be less sophisticated, could be advantageous (see fig. 6.3). Furthermore the positioning of objects during transport needs to be considered. Stability would be better maintained if heavy loads could be held at the center of the robot base instead of in front of it as is the typically solution with today's EOD robots. Currently available robots are around 10 times heavier than the objects they can handle[10].

13. Multi-role capability: As carrying a robot during MOUT results in a considerable additional load, the benefit it brings is of special importance. The robot has to be used often enough to justify itself. This implies that it has to be used for multiple purposes which call for multiple payloads. The complexity of payloads ranges from simple solutions such as two-way audio or fire circuits, to payloads requiring real-time data processing, or high speed data transmission to the user-interface. Weapon deployment against humans is of interest in MOUT. Within EOD and firefighting weapons are used against objects. Non-lethal weapons are de-

[9]In robotics the term manipulation is used for the task of handling objects with a gripper on a robot arm.

[10]For example the Andros EOD robot can lift 8% of its own weight with the arm at full extension (Remotec, 2007), the Defender 11% (Allen Vanguard, 2007).

Figure 6.3. Even though it was possible to open the trunk of the car (the springs holding the hatch open were broken) the robot was unable to perform any further actions. Instead a bomb technician had to approach the site to perform the trivial task of putting a stick under the hatch to keep it open. A second, even primitive arm would be of great value on EOD missions.

sired both by the military and the police. In other applications than MOUT, where the robot can be transported in vehicles without much effort, it is to some extent possible to have several specialized robots available. Although both cost and practical issues will favor multirole capability, CBRN robots need to be able to carry a number of different sensors.

14. Radio range: The range of wireless communication restricts all groups. Of the investigated applications, firefighting and SWAT are probably the least demanding. Military and public safety authorities typically have access to reserved radio frequency bands and are permitted to use increased transmission power. Unfortunately, there is no global standard, but a facility to adapt robot communication to national legislation could be a way to address the issue of wireless communication.
15. Usability demands: Usability incorporates both the physical handling of the system (robot, user interface and accessories), and the mental process of controlling the robot through the user interface. The need for more feedback, refined interface designs, and autonomous operator support is shared by all groups. Some

of the improvements are technically simple, but would still be if great advantage. MOUT includes the most demanding circumstances for the robot operator. Surrounding dangers, high workload, frequent relocations, pressure of time, and the risk of providing comrades-in-arms with false information or even executing lethal actions all contribute to the demand for high usability. In the other applications operation is less physically and mentally demanding since a robot can be controlled from a *safe spot* and primarily material damage is at stake. The availability of a *safe spot*, in addition, has a positive impact on the operator-to-robot ratio, since a it eliminates the need of personnel handling the close up safety.

16. Reliability: High-risk workers require reliability, since, for their personal safety, they depend heavily on their gear, well-practiced procedures, and team work. Many actions in MOUT are especially critical, as they involve revealing one's presence, or intentions, to the enemy. Such actions must therefore succeed on the first attempt. In the applications of the other groups alternative methods can be deployed if the robot fails. The reliability demand not only includes hardware, software and work procedures, but also services such as technical support, maintenance, modifications, and access to spare parts/replacements.
17. Development of robot work procedures: EOD, CBRN and firefighting missions target artifacts or substances while the other two are directed towards people. MOUT and SWAT, in addition, are team efforts while the tasks of the other groups are to a larger extent are carried out individually by a small specialized team.
18. Compliance with standards and other systems: The importance of considering integration with other systems early in development cannot be underestimated. Post-adaptation may be costly, influence performance, or, might not even be possible. The high number of military requirements (MOUT, EOD, and CBRN) will probably require greater efforts than the area of firefighters and SWAT. Successful integration requires consideration of a broad range of issues such as, the power supply, radio communication, maintenance, and command and control (for examples see 4.3).
19. Mass production: If it was decided to deploy robots on a large scale, SWAT, EOD, CBRN and firefighting in Sweden would require fewer than some twenty or thirty robots each. The number of units needed for application in the infantry could be up to a couple of hundred. Public safety authorities are commonly organized in shifts in order to provide constant service. Military units are to a greater extent deployed as an entire unit with periods of recuperation in-between.

20. Price sensitivity: The investment costs for EOD robots can be justified by long-ranging successful deployment and because the number of systems needed for traditional EOD teams are relatively few (the total cost of acquisition is not dramatic). Similarly, there is probably a higher tolerance towards costs in the CBRN area since it requires few systems and as it is already recognized that this work requires expensive sensors, etc. When it comes to military units, which occur in large numbers, the cost per unit will be an important issue, especially as the robots may be lost in large numbers. Public safety authorities such as SWAT and firefighters are required to provide a cost-efficient service which calls for a sensible relation between cost, performance and the deployment rate.

Contradictory Criteria

When comparing the different criteria, it becomes clear that some of them contradict each other One of the most obvious examples is for a robot to be man-portable while still being able to handle heavy loads. A systematic comparison[11] of all 20 criteria shows the pairs in columns I and II of table 6.2 to oppose each other.

The justifications for the priorities in table 6.2 are:

A – D	Robot arms of any size add weight.
E	The smaller a robot is, the more it is challenged by obstacles.
F	Man-portability challenges user-interface design as in- and output devices are limited regarding size, weight, power supply, processor power, etc.
G	Ruggedness adds weight.
H	Smallness and light weight makes it harder to achieve high speed.
I, J	Having several payloads and providing more energy adds weight.
K – O	The more complex a system is the harder it will be to ruggedize.
P	High speed generates noise and causes increased thermal signature through thermal losses.

Comparison

As can be seen from table 6.2 the criteria of *man-portability* and *ruggedness* are particularly constraining for MOUT robots. It should, however, be possible to deal with these and other contradictions (marked *I&II* in the MOUT column of table 6.2) by means of a careful design which takes both criteria into account.

[11] By morphological analysis.

Table 6.2. Column I and II show the criteria found to be contradictory. A *1* in column III shows the criterion to be incompatible, a *2* indicates that they are in opposition and therefore have to be carefully considered. The MOUT, SWAT, EOD, CBRN and firefighting (FF) columns show whether any of the criteria in columns I and II were rated as crucial (rated *1* in table 6.1).

	I		II	III	MOUT	SWAT	EOD	CBRN	FF
A	**Access housing & offices**	**vs.**	**Heavy manipulation**	**1**	**I**	**I**	**I**	**I**	**II**
B	Man-portability	vs.	Light manipulation	2	I		II	II	II
C	**Man-portability**	**vs.**	**Medium manipulation**	**1**	**I**		**II**		**II**
D	**Man-portability**	**vs.**	**Heavy manipulation**	**1**	**I**				**II**
E	Man-portability	vs.	Off-road ability	2	I&II				
F	Man-portability	vs.	Usability demands	2	I&II				
G	Man-portability	vs.	Ruggedness	2	I&II				
H	Man-portability	vs.	Robot speed	2	I&II				
I	Man-portability	vs.	Multi-role capability	2	I&II	II		II	
J	Man-portability	vs.	Power endurance	2	I	II	II	II	II
K	Ruggedness	vs.	Multi-role capability	2	I&II	II		II	
L	Ruggedness	vs.	Transport and drop	2	I&II	II	II		
M	Ruggedness	vs.	Light manipulation	2	I		II	II	II
N	Ruggedness	vs.	Medium manipulation	2	I		II		II
O	Ruggedness	vs.	Heavy manipulation	2	I				II
P	Robot speed	vs.	Stealth	2	I&II				

Some of the other contradictions are, on the other hand, harder to satisfy. Of the sixteen pairs three were decisive (rows *A, C,* and *D* in table 6.2), as they cannot be satisfied in combination. The priority for these criteria, therefore, will govern the extent to which the different groups can deploy the same type of robot. Table 6.3 shows an extract from the criteria in table 6.1 which are part of the three decisively contrasting pairs; the criteria rated *1* in table 6.3 shows that a single type of robot will not be able to satisfy the demands of all groups. MOUT tasks require a robot that is man-portable and can access narrow premises. SWAT teams have similar requirements, but have higher tolerances regarding *man-portability.* CBRN tasks can be fulfilled by either a small/man-portable or a medium-size/medium weight robot that is still able to access narrower premises. EOD tasks call for somewhat heavier manipulation in combination with still being able to access narrow areas. And finally, firefighting tasks call for handling heavy objects, which requires a robot that will be too large for maneuvering in tight spots.

The grouping of robots into three different sizes could be narrowed down to two if the EOD team can accept only being able to lift light objects while operating in narrow premises. If so, the demands of EOD could be fulfilled by two types, a small man-portable UGV with a light lifting capacity for operation in narrow premises, and a large sized/heavy duty robot for use in more open areas.

While there are distinctions amongst the five groups regarding preferable robot size there are, as well, many of the presented findings that are shared by them. For example, using the robot as a means of communication has been suggested by both the police and the military. Considering the robot not to be suited for the most offensive and time-constrained tasks is another similarity. This and previous work on SWAT teams have showed similar estimations of tolerable price, and the anticipated mental as well as physical demands that can be placed on the robot operator (Ciccimaro *et al.*, 2003). There are striking differences between the groups as well. While the MOUT users demand longer radio range and improved visual feedback, the police officers are generally satisfied with the robot's performance. Military users show a significant interest in weaponization, while the SWAT officers do not regard lethal abilities as a realistic application. *Combat reconnaissance* is of interest in MOUT while SWAT teams in general know their strike scene fairly well. Reduced risk and decreased weapon deployment are considered to be the primary benefits in MOUT. In SWAT, the system is seen as having the most potential as a tool for negotiation and surveillance over time. The level of acceptance versus criticism to new gear may be influenced by cultural differences within organizations. Traditionally the police, for example, have not had the resources to finance custom development, but been obliged to use COTS[12]. The military, on the other hand, have a history of technical development according to their exact specifications.

CBRN work shares many of the properties of EOD and is therefore a very promising application for UGVs (both target a specific area, decrease personal risk as well as mission time). The firefighters' handling of gas tanks is similar to the

[12] Components Of The Shelf

Table 6.3. The criteria, taken from table 6.1, which cannot be satisfied in conjunction, according to rows *A*, *C*, and *D* in table 6.2. The sizes of robots that fulfill the demands are shown in brackets. Abbreviations: S – Small-size and light-weight robots, M – Medium-size and medium-weight robots, L – Large-size and heavy-weight robots.

		MOUT	SWAT	EOD	CBRN	FF	ROBOT SPECIFICATION
1	Access housing & offices	**1**(S,M)	**1(S,M)**	**1**(S,M)	**1**(S,M)	2	Requires small or medium sized robots
3	Man-portability	**1**(S)	2	2	2	3	Requires small sized and light robots
11	Medium manipulation	3	3	**1**(M,L)	2	**1**(L)	Requires medium or large/ heavy size/weight robots
12	Heavy manipulation	3	3	2	3	**1**(L)	Requires large sized and heavy robots

handling of heavier objects performed within the EOD area.

In the vocabulary of organizational theory[13] UGV deployment in MOUT can be classified as reciprocal interdependent since the outcome of robot deployment on a significant part impacts on the own surrounding units. The actions of the other four groups are to a larger extent isolated, i.e. pooled or sequential. When considering introducing robots in new applications, the type of organization has to be considered since previous experience, gained under other organizational circumstances, may not be cross-valid. An example of a practical outcome from difference in dependence is time constraints, which are fundamentally different in MOUT and EOD. EOD missions are to a large extent performed by a small specialized team, requested to come and act independently within an area that has already been *seized* by another unit (no direct cooperation between the EOD team and the other unit is required). Robot missions within MOUT, on the other hand, to large degree will have to be carried out in synchronization with the surrounding unit.

Time pressure is an other difference. While EOD robots are considered to decrease time-on-target, the MOUT and SWAT robots will most often not reduce the operational time. In addition does MOUT and SWAT differ from the others by targeting humans rather than static artifacts. Dealing with dynamic targets conveys the fact that most often there is a chance for one attempt only. There will be no opportunities to fall back on traditional methods in case of failure.

The level of experience differs between the professions surveyed. Conscript-based military units stand out by having a low average age and lack of experience from real missions. Fear that having access to a UGV would make the personnel less willing to take risks was found only with the MOUT users and may be the result of the mentioned limitations. The significant difference in competence between officers and general enlisted soldiers enforces hierarchy. The higher experience within the other groups allows room for individual opinions and joint decision-making. Military units heading for an international mission face high uncertainties regarding the type of conflict, terrain and counterparts they will encounter. I.e. the foundation (in-data) on which estimations of beneficial UGV applications have to rest is weaker for the military than the other groups.

The awareness of risks and the obedience to procedures according to which high-risk situations are handled was observed to be high within the groups that encounter real risks on an every day basis. Firefighters, for example, never take risks by approaching a dangerous gas cylinder, and unless they can neutralize it they let it cool. Another example is SWAT work, which is regulated to such an extent that the officers perceive the risks imposed upon them by criminals as marginal. The MOUT unit, on the other hand, presents a quite different approach by defying

[13]Thompson defines three levels of internal interdependence between parts within an organization: 1. pooled, 2. sequential, and 3. reciprocal. Pooled interdependence refers to organizational parts that are not directly dependent on one an other in order to solve their individual tasks. Sequential interdependence occurs when organizational parts are required to act in sequence. Reciprocal interdependence includes situations in which the output of one part is the input to the others. The three types are, in the order indicated, more difficult to coordinate.

risks during training. Exploring the reason for their lack of concern is outside the scope of this thesis, but can be noted that the phenomena may suppress interest in risk-reducing technology.

6.2 Changing the Doctrine

As with many professions the prevailing MOUT doctrine has evolved through small iterations over a long period of time. The main tools in use such as assault rifles, grenades, combat vehicles, portable radios, mines and anti-tank weapons have all been around for 50 years or more. EOD and mine-clearance robots are also used on a regular basis to solve well-defined tasks according to highly-developed methods. Robots in other applications, on the other hand, constitute an entirely new functionality which holds the prospect to set aside many of the constraints that have shaped prevailing tactics. This thesis shows that it is possible to change well-established and highly structured doctrines to incorporate new concepts, but that it will require a larger tactical development than what is normally accomplished with the users' development assets (military tactics are normally refined by small changes over long time). The incorporation of new technology can be divided into two categories:

1. Tasks performed today for which robots could replace humans. This category, for example, includes the demanding and often time-consuming clearing of IEDs or mines. The EOD teams typically first try to use the robot in order to avoid personal risk. If this does not succeed, they will proceed to solve the situation manually under the protection of a bomb site.
2. Tasks that are not performed today but that could be accomplished using robots. Again, IEDs and mines can be used as an example, but in that case when encountered by others than EDO teams. According to current strategy regular troops do not attempt to disarm or pass encountered IEDs or minefields. Instead they are forced to find an alternative route or make a request for an EOD team to clear a passage. Equipping regular units also with EOD robots could enable a complete change of some aspects in the current doctrine.

During the investigations it appeared that scenarios falling into the first category were more concrete and, therefore, best suited for initial implementation. It meant taking an established behavior in current use and modifying it to include robots. If the new behavior were to fail, the traditional methods could be used for recovery. However, gaining insight into the full potential of new technology by including the second category would require a substantial redesign of doctrines, including identification of niches that may not have been targeted before. The opportunity to test previously non-existing capabilities may not occur during current tests and training maneuvers as they are typically arranged to suit existing methods. Applications that fall into the second category would result in behaviors that lack traditional alternatives, thus making the user wholly dependent on all-new features. During the process of introducing new capabilities, it should be kept in mind that traditional methods may be set aside, which calls for reasoning about how to act if the new feature were to fail.

6.3 When to Test

There are numerous examples, not only in the robotics area, where technologies are pushed as well as pulled into application without any preceding user tests. The products that manage to survive on the market typically undergo iterative improvements through the release of upgrades or better versions. If viewed from a larger perspective this can be seen as finally having the user in the product development cycle. Apart from not being the most cost and time efficient strategy (Bias and Mayhew, 1994), this way of working conveys a number of issues critical for the robotics community.

From the legislative aspect of introducing unmanned systems into traditionally manned domains such as traffic, a history of failed attempts to demonstrate performance and reliability will be an obvious burden. Further, early users will inevitably form an opinion about the systems they deploy. Unsuccessful products may cause long-lasting negative impact which can be very hard to recover from. The same holds for the impressions amongst those in charge of funding for research and development. This makes the issue about when to introduce or test new robotic features a complex matter. The more developed the introduced system is, the more relevant the results are likely to be. In a conflict, there is a need to carry out testing during early stages of the product design. Early introduction, in addition, enables parallel development of the system and the tactics for use. If this includes changing well-established doctrines it may be a process that requires significant time.

Once having access to working prototypes and methods that allow for realistic user testing, it may be assessed how often the robots are actually deployed and what benefit they convey. Realistic tests also enable estimation of costs for maintenance, tactical development, training, etc. Hence, the cost-benefit analysis to settle the question of whether acquisition is justified can be carried out. However, analyzing the advantages of UGVs in high-risk applications is not only a matter of tactical, technical and economical considerations. The valuation of, for example, the investment in UGVs that can be afforded in order to decrease mortality calls for both ethical and philosophical reasoning.

A comparison of the project phases exploring the ATRV and the Packbot shows a clear distinction between the levels of user involvement that the tested systems allowed for. The non-suitable properties of the ATRV distracted the military from evaluating the features the researchers wished to display. At that point the development team considered repainting the robot and disguising the absent properties in other ways, but instead it was concluded that while it is possible to demonstrate technology at this state of development, it does not provide opportunity for *hands-on* experience. A property of end-users is their tendency to focus on any possible flaws in a system since they are the ones that will have to cope with them in the event of product realization. Researchers, on the other hand, are prone to having the opposite viewpoint, shedding light on any feature that may be developed to become a functioning utility. The cultural difference between end-users and researchers should not be underestimated. Camouflaging deficiencies and raising false expectations has been a common measure within robotics in the past. Doing so is, however a short-sighted act that hinders UGV development on a long term. A clear distinction between user testing and demonstration must be made and the target group must be made well aware of the scope and purpose. It is likely that performing the two phases in the opposite order would have made the military users better suited to evaluating the features of the autonomous functions. But the way the project turned out, the main benefit of the initial attempts was to demonstrate isolated capabilities for decision-makers as regards research funding and procurement.

The main trials on the other hand, permitted end-user testing and the definition of a baseline for UGV deployment within the police and military. The Packbot Scout was found capable enough of serving as a basis for research concerning: search for objects, exploration, mapping and payload delivery. Issues regarding mobility, endurance, robustness, radio range, user interaction, tactics, organization and ethics concerning arming robots could be successfully explored. On request, the users had the ability to see past properties that restrained the system, for example the bulky operator laptop. On the other hand, implementation of the Packbot did not enable the users to provide a valid opinion on topics such as autonomy or sensor data fusion. Nor did the end-users have enough background knowledge to value the system in economical terms. It seemed more natural for them to value the benefits of the robot in comparison to other equipment.

The user investigations gave an opportunity to gain insights into the physical and mental resources available amongst the users. The tests also built a cooperation framework between the participating organizations and served as a suitable way to initiate the use of robotics in the addressed areas. Man-portable platforms were a suitable first step in the introduction of robots amongst high-risk workers. Dealing with larger platforms, potentially with a more advanced autonomous functionality, will significantly increase demands for testing by orders of magnitudes due to safety regards, legislation, and practical issues such as transport, towing, fuelling, training, and field repairs.

After having carried out trials that demonstrated utilities useful to the test groups, they expect the UGV activities to continue and that they ultimately will be provided with the new tools for use during real missions. The MOUT company, for example, is scheduled for participation in international missions from April 2008 for which they wish to be provided with robots according to what has been tested. Not continuing the successful trials will, from an end-users perspective, be regarded as a refusal to give priority to the discoveries they have contributed to, as well as the importance of the tasks they are assigned.

6.4 Implementation

Achieving tests at one specific organizational level calls for the framework of at least one level higher, while testing squad behaviors requires the framework of a platoon, assessment at platoon level, in turn, calls for the surrounding action of a company to form a realistic setting. I.e. the majority of the participants provided the context for the tests rather than interacting directly with the product.

The approach taken – user-governed testing in realistic settings – involved having to deal with many factors complicating data collection. Direct investigation of deployment in real missions is often prevented for reasons of safety or secrecy. Fortunately, high-risk workers commonly train under realistic conditions which provide the opportunity to perform direct data collection. It should, however, be kept in mind that training maneuvers probably differ from real missions regarding such as mission profile and willingness to take risks which was the case for the main trials.

Carrying out tests within the ordinary activities of high-risk workers imposes strict demands on the gear being tested in terms of reliability and ruggedness. Even though test persons can be asked to oversee some undeveloped features hindering the tested product, the greater the anticipation required, the less valid the results. The overall approach was therefore only to consider functions that could be provided in reality or simulated with reasonably realistic mock-ups. Despite dealing with high-risk workers, making sure the trials do not cause any material or personal damage is as important as with users in general. Handling safety in a highly unstructured field setting may require even more attention.

Using the users' ordinary activities as a base entailed the participants having first and foremost to solve their regular tasks while considering research as a subsidiary matter. As a result the respondents – key persons such as commanders in particular – had limited time to set aside. Participants in military maneuvers are constantly graded, and leaders who attempt to deploy new features, instead of using traditional methods, take an increased risk of failure. The SWAT team selected for trials was similarly being observed by the other teams during the tests. Establishing a tolerant, supportive, and rewarding atmosphere during future tests will increase the rate of deployment.

In addition to the soldiers selected as operators, an officer was trained to operate the Packbot during the MOUT study, simply because officers are accustomed to mastering all the skills of the soldiers. Having an officer trained denoted knowledge at a high level of the robot system's capacities during tactical planning and briefing. The trained captain was the company's second in command and hence a key person within the unit.

The ATRV trial shows personnel carrying out high-risk tasks in general as showing a reserved attitude towards new technology until they get to fully know the system's capabilities. The hand-over of the Packbot to the MOUT and SWAT users, rather than bringing it to each appointed trial, was intended to give them a sense of responsibility and thereby increase their commitment in deployment. Still, the study showed that implementation of a robot required significant efforts for the development and training of new behaviors. Specific support and coaching will be required to enable this. Simply providing a user with hardware will not be sufficient to implement robots in-depth within teamwork applications requiring complex human-robot and organization-robot interaction.

6.5 Collecting Data

The course of events during large scale training maneuvers is highly dynamic and can scarcely be anticipated, which puts special demands on flexibility during data collection. In addition, some groups, for example the military, act in a large and complex context (enemies and other unites of one's own) which, if not present, must be simulated, in order to achieve a realistic test setting. In such cases proper evaluation calls for an approach which considers the robot as a component in a system rather than as something that can be studied in isolation. To a large extent, qualitative approaches were considered to be the best option when testing in large and complex settings such as operations including several hundred persons acting individually and dynamically on a mutual task. This is because such a complex environment is unsuited for quantitative measures as it can scarcely be kept constant, or because the investigated phenomena do not occur often enough to be statistically verified with adequate confidence. Further, it is not possible to perform repeated trials in the same test environment with a single user group without offset due to learning effects.

Regardless of what methodology is applied during the phases of research and development, most of the army's evaluation is carried out through *participatory observation*, i.e. an embedded observer (the officers and soldiers) uses gear on a daily basis and forms a subjective personal opinion. Hence, even if it may be argued that qualitative approaches have their limitation, they correspond to how fielded products will be regarded once deployed for real.

Manuals and instruction videos allowed access to basic work procedures and terminology. As may be the case for many professions, the documentation mainly covered the basics. Observation and participation were important means for gaining a holistic view of the users' work practices. Participation allowed a valuable opportunities to experience the users' situations and encouraged spontaneous discussion. Continuous presence, conforming to the same restrictions, and sharing the same hardships as the soldiers were important ingredients in building up the military respondents' trust and commitment into the project

The unstructured interviews conducted during the maneuvers were important in getting to know the users and their activities. The short moments of conversations in the field, however, did not allow for reflections. The ten interviews at the end of the main study served both as a recollection of the performed missions, and as a survey of opinions about the system. Follow-up questions were used to verify the validity of the responses, which made it possible to evaluate areas where the users had well-grounded opinions. The respondents showed a high level of cooperation and willingness to share knowledge. Using an interviewer who had not participated in the field study decreased the risk of bias. The interviewer's little previous knowledge did not seem to cause friction with the respondents, but resulted instead in more detailed and descriptive responses, which opened for the possibility for additional discoveries. The aim of the questionnaire was to document the performed robot missions as well as to validate previous findings (from e.g. interviews) by increasing the number of respondents. Both the final interviews and the questionnaire indicated which topics the users could evaluate with validity.

Whilst considering user-evaluation based on self reporting inquiries[14] (which, for example, was the only option for investigating the SWAT police), it should be remembered that respondents are inclined to provide the inquirer with an answer, no matter their amount of experience. I.e. although results are firmly based on users' opinions or behaviors, they may be lacking in validity. An important quality of long-term testing is the decrease of bias connected to the introduction of a new product. Long-term trials give the test group a chance to modify their behaviors to the new tools and to form a mature opinion (Nielsen, 1992; Preece *et al.*, 2002). At the beginning of the MOUT tests, views on the system's capabilities and possible applications differed vastly between users. The initial interviews with the two officers produced numerous suggestions as to how the robot may be used in urban warfare. Most of these proved unfeasible during later trials. Similarly, the unstructured interviews made during the trial illustrated that many of the suggestions of how to deploy robots were unrealistic. Not until the end of the deployment phase, when the final interviews were conducted, were the officers and soldiers experienced enough to reflect on robot deployment with greater agreement.

Another strategy for judging the validity of the results was to investigate the same topics by several methods so as to enable verification by triangulation (Silverman, 2006). During the SWAT study it was not possible to gain data from several parallel methods to check validity through triangulation. As indirect observations were the only source of information, it would have been particularly beneficial to have a large data set, i.e. many operators with extensive experience. Unfortunately, this was not possible. Only two respondents were available and their experience, despite the five month trial period, was limited. In addition, there was an obvious risk of bias between the respondents since they worked together.

The circumstances of the field users posed problems not only for the tested equipment, but for research as well. Carrying out genuine *field work* on high-risk workers entails sharing their capabilities in all weathers, long working hours, off-road mobility, and being self-sufficient both in terms of personal and technical needs, for periods of several days (accommodation, clothing, supplies, safety gear, batteries, etc.).

The monitoring of a group as large as a company entailed a number of practical issues as well. Targeting highly unpredictable activities often leaves no other option than being continuously in place and ready to act as opportunities arise.

[14]Data collection based on the users' conception of the investigated feature

Selecting the target for observation is a delicate matter. Monitoring large, dynamic organizations, distributed over complex geographical areas can be very demanding. The target of observation has to be shifted frequently in order to capture the overall situation. Attending briefings is a good way to gain knowledge of the outlined plan, although the course of events often takes another turn. Having access to radio traffic and being able to reposition swiftly, both on foot and with vehicles are important facilities for real time coverage. Managing transport along with combat vehicles can be particularly demanding, especially when the troops are dropped off and picked up repeatedly leaving the researchers' vehicles behind. Being granted permission and receiving training to ride along in the combat vehicles can be a great advantage. Observing the process from the enemy side in parallel is a way to obtain additional information.

Documentation was challenged as well and photography proved to be the most valuable feature out of note-taking, photography and video recording. Real-time note taking was often impractical. Despite extensive efforts, for example by handing out camcorders to the military training officers or using helmet-mounted cameras, video recording in general captured little valuable information compared to the workload and distraction it imposed.

Chapter 7

Conclusions

This thesis has investigated the use of man-portable robots as a tool for high-risk workers in urban terrain. MOUT has been the application in primary focus and the SWAT police was considered as a second target for investigation. In addition firefighters, CBRN and EOD teams were surveyed in order to examine the extent to which the MOUT and SWAT findings had validity also for other high-risk professions. The main questions at issue were: what are the key user characteristics? how can they deploy robots,? and what are their technical demands on the robot? The MOUT and SWAT investigations were carried out by letting a Packbot Scout be an ordinary piece of equipment over an extended period of time.

This chapter starts with a brief presentation of the findings from each of the five user groups. Then the level of conformity between the groups is described. A reflection of the thesis completes the chapter.

7.1 MOUT

The MOUT findings are based on two years of cooperation with the 6th Urban Warfare Company of the Royal Life Guards. Two sets of robot tests (3 and 6 months, respectively) were performed during which the robot was implemented within the ordinary organization and deployed as a standard piece of equipment during training maneuvers. The long-term approach in a realistic setting enabled investigation of tactical, ethical, organizational, technical and interaction issues from the users' perspective. Data collection was achieved by interviews, observations and a questionnaire. The responses from the test participants changed to be more uniform over time and it seems reasonable to believe that the increase of agreement indicates the end-results to be valid and can serve as a foundation for future work.

The study showed that the MOUT units rely on precise and thoroughly practiced actions that can be executed with high precision and a minimum of ambiguity. High risks and uncertainty makes reliability important. Time is often a critical issue and means of communication are often sparse. All MOUT gear must be portable since many of the missions are performed on foot, which also make ruggedness and weight important issues. Equipment is expected to function no matter the weather or time of day.

Deploying the Packbot in MOUT is a two-person task both for physical and mental reasons. The most common mission was *combat reconnaissance* in buildings when an enemy presence was uncertain and time was not critical. The main benefits were decreased risks for one's own troops and civilians as well as reduced weapon deployment. The users were of the opinion that units given high ambition tasks in urban settings should be equipped with one UGV per platoon. A decision to acquire UGVs for all regular troops would call for proportionately high numbers of robots and real deployment might involve include substantial losses.

The range of the radio link, the video feedback, and the design of the operator control unit were the features most constraining to the tested system's overall performance. Other properties of the system, such as ruggedness, size, weight, terrain ability and endurance, on the other hand proved to be suitable for the application. During the training maneuvers, which tended to be offensive, the Packbot was deployed between two and ten times a day. Trials with payloads indicated that the system has potential for more frequent deployment if extended with modular add-ons. The tactical impact of UGVs changes drastically when given lethal abilities. The military did not consider weaponizing robots unethical as long as the fire commands were executed by humans (not autonomous). Integration with other military equipment is important for the users' overall performance.

The question of beneficial deployment is however beyond just technical functionality. The introduction of robotics as a tool to infantry soldiers may be a step as large as those of automatic rifles or portable radios. Implementing a device with a functionality as novel as a robotic device will require tactical adaptation beyond the tactical changes normally accomplished from one year to another. Those who begin implementation early will not only gain the benefits of today's available systems but also be able to carry out tactical development in parallel with ongoing technical developments and thereby shorten the time to deployment of the next robot generations.

7.2 SWAT

The SWAT study included giving a SWAT team (8 officers) access to the Packbot for a period of five months. During the test the team trained with the robot on a weekly basis and they brought it with them on about half of their turn-outs. The robot got to be deployed for real on one occasion to investigate a suspected bomb. Data collection was performed through interviews in the beginning and end of the test phase.

The SWAT police did not consider risk reduction to be the main benefit of the robot. Nor was it of interest to give the robot lethal capabilities such as suggested for MOUT. Instead it was considered that the robot could provide increased information and substitute for personnel in dull tasks. Approaching suspects with the robot as an excuse to communicate or deliver items, and at the same time observe the surroundings, the suspects, hostages, etc. was considered to be the most appropriate use. Once in place close to the suspects the robot could, if equipped with non-lethal weapons, be used for distraction when performing *break-ins* and arrests. Long-time surveillance was, additionally, considered a possible application (requires motion detection). The investigated users were in general satisfied with the performance of the robot. Two-way audio, an increased field of view, motion detection, and the possibility to store images for later viewing are desired improvements.

The tactical needs of the Stockholm unit could be fulfilled with one robot. A fairly rough estimation of deployment frequency indicates about 20 times per year. Acquisition is the primary cost connected to the introduction of systems such as the Packbot for the police. Costs for training, basic maintenance, and tactical development can be handled through available resources with slight expansion. The users estimated a tolerable price limit to be USD 30,000-50,000.

7.3 Firefighting

The firefighters were investigated during a one day visit to the Södertörn fire station. The visit included interviews with two senior firefighters and a demonstration of the robot (a tele-operated, gasoline powered, tracked robot 1 m wide, 1.8 m long, 0.7 m high, weighing 550 kilos). The objective in this application is to make acetylene cylinders that have been exposed to heat accessible for neutralization by puncturing with rifle fire. An acetylene cylinder that cannot be shot at has to cool for 24 hours during which an area of a couple of hundred meters around it has to be sealed off. The cylinders weigh up to 70 kg and are mostly found in workshops or on construction sites. Main features desired for the robot are: power endurance, the ability to grasp and move heavy objects, and a reliable radio link. Several fire stations can share a robot as about 20-25 situations involving acetylene cylinders occur per year in the Stockholm area.

7.4 CBRN Contamination Control

The CBRN application was surveyed by interviewing two officers to the CBRN development group at the CBRN Center of the Armed Forces. The task of the investigated Light-role CBRN team is to go into contaminated areas wearing protective suits to deploy assorted sensors. The robots in this application need to be able to access all kinds of premises, have several hours of power endurance, and possibly have an arm in order to reach out with sensors or to gather samples (light weight). Methodological and tactical development is required as this application is rather unexplored. Robots hold the prospect of shortening mission time, increasing endurance, and reducing personal risk as well as the need to decontaminate people. The number of systems required on the market is fewer than for MOUT and EOD.

Shortened mission time and reduced risk are the main benefits of robots in this application.

7.5 EOD

The use of EOD robots was investigated by a two day visit to the Army EOD and Demining Center where both the military and police bomb technicians are trained. The visit included interviews with experts in the field and observing the training of robot operators. Military and police EOD teams are similar in terms of their gear and working procedures. They use robots as a key feature and have long experience of everyday deployment. Tasks which cannot be executed with robots (approximately 40 %) have to be addressed by persons and include severe risks, and the emphasis is on precision rather than speed. The hazardous objects are either destructed in place or moved which requires a robot arm for aiming disruptors, placing demolition loads, or picking and placing the object with a robot arm. Key features for robot deployment are: the ability to access housing and offices, power endurance, reliable radio communication and the capacity to handle light to heavy objects (50 kg). The police bomb squad in Stockholm carries out approximately 130 missions per year, only about 10 of these involve actual explosives. The recent military conflicts show an increased need for EOD capacities, a demand that is to large a extent being met with compact sized EOD robots (e.g. iRobot Packbot EOD or Foster-Miller Talon) which share many of the properties desired in MOUT.

7.6 Comparison

High-risk workers in general perform under highly uncertain conditions and are therefore reluctant to introduce any new uncertainties. I.e. they demand their gear and methods to be well adapted to the application and very reliable. Further, all the groups investigated act in an urban environment which includes passing narrow sections such as doorways or furnished rooms. UGVs addressing these applications therefore need to be reliable, compact, and mobile. The ability to pass steps or stairs constitutes a minimum level of off-road performance in order to achieve a cost-efficient deployment frequency. As no robots are able to match the mobility of humans there is no other option for the applications with higher demands on mobility, such as MOUT, than to use man-portable platforms. The power endurance of today's systems, generally one to three hours, seems to meet the demands of the ways UGVs will be deployed initially (future abilities may enable robots to perform missions over a longer period of time). A modular system that allows for adding assorted payloads is required as the different professions all have their own payload demands. Robots should in addition be adapted to the existing infrastructure, particularly in terms of power supply, communication, and command-and-control. This becomes especially important for such as the military or rescue workers who operate away from civilization.

Wireless communication stands out as a limiting factor, particularly in MOUT, EOD and CBRN applications. Robustness is another important property for field applications since operators that are required to move swiftly, such as in MOUT, will be unable to handle gear with care. UGVs need to be as sturdy as the users' other equipment. Within EOD, CBRN and firefighting missions it is essential to solve tasks with precision rather than with haste. In MOUT, on the other hand, rapid action is often considered a tactical necessity. Unfortunately use of a robot involves a reduced pace and can therefore only be considered when time is not critical. The pace of robot missions is, generally limited by the operator's ability to gain situational awareness and to control the robot, rather than by its top speed.

The ability to physically interact with objects is an absolute requirement for EOD teams and fire fighters. Simply localizing and inspecting the hazardous objects is not sufficient. An arm would be of benefit in the CBRN application also since some sensors require close positioning or sample-taking. EOD and firefighting share the need to handle heavier objects while CBRN teams only require light weight capability. In SWAT and MOUT applications a robot arm could be of use, but is hard to combine with the demands for robustness and light weight, which are of greater importance.

When comparing the different groups it becomes clear that a few non-negotiable constraints, which can not be fulfilled in combination, come to determine the extent to which the groups can deploy the same type of UGV. Comparison of the five groups' criteria shows that three sizes of robots are required to fulfill the assorted needs. The MOUT troops require a man-portable robot, which can also satisfy the CBRN team (small man-portable robot with a light lifting capacity). A man-portable robot is, however, not able to handle the larger weights encountered in EOD or firefighting (medium-size and medium-weight robot). On the other hand MOUT, SWAT, CBRN and EOD all share the desire to be able to go into narrow premises, something that is not so essential for firefighters (large-size and heavy-weight robot). The three types could be narrowed down to two with some sacrifice of the EOD team's lifting capacity while operating in narrows.

The MOUT test participants support acquisition of a system such as the Packbot for combat support. SWAT and CBRN do so too, given that the systems are adapted to their most fundamental needs (2-way audio and non-lethal weapons for the SWAT police and appropriate sensors together with a design that facilitates decontamination of the UGV to achieve CBRN capability). Of the five groups only the MOUT application has any prospect of requiring higher numbers while the other groups have a national need for some twenty or thirty UGVs.

7.7 Reflection

The approach taken proved to be a suitable way to introduce unmanned vehicles in organizations dealing with high risk[1]. Long-term deployment gave respondents a possibility to get closely acquainted with the robot system and to use it on their own terms. The compact system allowed for realistic and complex trial situations within ordinary activities while still maintaining safety. Selecting a small platform also enabled low costs and convenient testing. The work performed provides a pilot example to indicate future research issues as well as future branches of UGV implementations.

The difference between the training maneuvers and real missions (both out of content and tolerance towards risks) may be the methodological weak point of the MOUT investigations. The interplay between the robot and those it would encounter (e.g. bystanders, suspects, victims) stands out as the most significant open issue deriving from the SWAT study – little experience of real deployment and only having two respondents are the primary limitations. The survey of the firefighters, EOD teams, and CBRN units were of limited depth and, just as for SWAT, rely heavily on a few respondents' subjective opinions.

The approach to have the end-users deploy the tested system in a realistic setting limited the scope to technology that could be operated by soldiers and also have a fair chance to hold out in harsh environments. The requirement to identify reasons justifying continued use of robots has favored applications that could show immediate success over applications which require more extensive innovation, even though the latter may have had greater long-term potential. As a consequence this work has focused on robot applications that could be implemented and tested. It is likely to assume that there remain other, more complex and beneficial ways of application to be discovered. Achieving the latter will, however, require cooperation in-between all parties with an influence on UGV deployment (research and development, industry, procurement, politicians, legislative powers and end-users).

Despite the sources of misalignment and reported limitations, the project indicates that robots will become a standard utility in many high-risk field applications. In order to deploy the new technology, the organizations concerned need to develop their routines and procedures. In most cases, the robot system cannot just substitute for an individual and it will not be isolated and independent, but rather a component that has to function in cooperation within a complex framework. Current working methods have to be revised in order to fulfill the requisites for UGV use, a process that should be performed in parallel with technical development. Once made available for efficient deployment, it will become ethically, economically and politically unjustifiable not to make use of robots during high-risk missions.

[1] The 6th Urban Warfare Company is continuing to train with the Packbots and wishes to take robots with them when going on international mission in April 2008. The SWAT unit is currently filing a request to the national police board to be granted continued exploration of tactical UGV deployment. The SWAT police, in addition, has an interest in exploring the use of UGVs for CBRN exposed missions.

Appendix A

Appendix

A.1 Experimental Design

The Robot and the Operator Control Unit

The experiment was carried out with the Packbot Scout without the flipper arms mounted (see fig. A.1). The flipper arms were excluded in order to make robot operation easier and the test course did not contain any steps. The iRobot laptop OCU was placed on a desk during the experiment (see fig. A.2). During the experiment the user interface was set to only display video from the wide-angle camera with a resolution of 240*320 pixels at a frame rate of 15 frames per second. The wide-angle camera was chosen as it simplifies maneuvering through narrow passages, which is especially advantageous for novice operators. In order to simplify the human robot interaction none of the other sensor data were displayed and the robot's top speed was limited to 0.7 m/s.

Test Persons

The test persons consisted of 12 men and 8 women, who were evenly divided between the robot group and the non-robot group. The test persons ranged in age from 24 to 50 years. They all had a college or university education but in varying subjects. Also their professions varied. They were all frequent computer users but not experienced robot operators or RC-pilots. The test persons had not visited the explored area before.

The Explored Region

The test was carried out in a 36 meter long corridor with 15 closed doors and two open doors leading into two shower rooms. To make the setting more complex two temporary walls were mounted at the one end (see fig. A.4). The explored premises

Figure A.1. Front view of the Packbot. The flipper arms were not mounted during the test.

Figure A.2. The Laptop user-interface in the experimental setup.

were well lit with fluorescent lighting, had no windows and were nearly free from obstacles such as furniture.

The robot-operating group carried out their task from a room nearby the explored region. The room was out of sight but within reach of the robot's radio-signal. The non-robot operating group carried out the mapping while walking around within the area.

Test Outline

The test was carried out according to the following steps:

1. Briefing: Informing the participants about the experiment.
2. Pre-questionnaire: Handling personal data, experience of robots, tele-operation, joystick control, maps and drawings.
3. Robot training (only for robot operators): In order to ascertain the robot operators to have reached a lowest level of driving skill prior to the experiment, they were given a short driving course and had to pass a test. The training involved two minutes of driving practice and was followed by a short test along a course similar to the experiment area. The test was repeated until it could be carried through without collisions. All the robot operators passed the test on their first or second attempt.
4. Map-drawing instructions: In order to simplify evaluation the test subjects were only allowed to draw on the lines on a cross-ruled sheet of paper. The scale was set to three checks to a meter and the test persons were instructed to round the dimensions to fit the closest cross-rule line. Only walls and doors were to be depicted, using given symbols (see fig. A.3). The test persons were instructed to do the mapping from one end of the area to the other. They were instructed not to return to previously mapped areas unless these areas led to unexplored regions. The task was to be fulfilled as quickly and as accurately as possible. The non-robot operators were instructed to move at normal walking pace. Both groups were instructed to return (themselves or the robot) to the starting point after having covered the whole area.
5. Map-drawing training: The map-drawing training was carried out in order to make sure that the mapping-instructions were understood and to give the test subjects a chance to practice and ask questions before the start of the real test. The training included exploring and depicting two rooms in the same way as during the experiment. After that, the map was evaluated with the test leader.
6. Experiment: The mapping task started at the lower end of the corridor (see fig. A.4). The maximum time for the mapping was set to one hour, although the test persons were not told in advance.
7. Post questionnaire: Handling the test person's experience of the test.

A.2 Analysis and Results

The produced maps (see fig. A.4, A.5, and A.6) were divided into sub-elements in order to facilitate analysis. Each element had a specified length and was either a wall or a door. The elements started and ended where there was a change of element type, in corners or at wall ends (see fig. A.3). The correct version of the discretized map contained 112 elements (see fig. A.4).

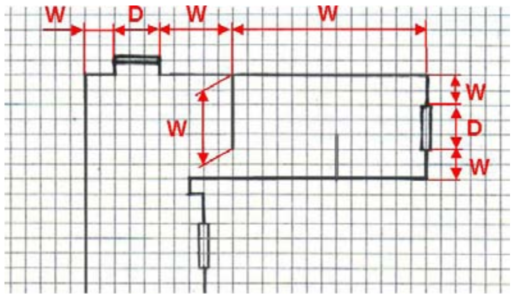

Figure A.3. The principle of the dividing the maps into sub-elements. W – wall elements, D – door elements.

The tests were evaluated for time consumption, error rate and accuracy. All evaluation criteria were considered as an average per element. Absolute measurements, such as total time used, were not applicable for comparison since the test persons did not draw as many elements in their maps. Hence, time consumption too was considered as the average time in seconds per depicted element. The error rate was regarded as the percentage of erroneously drawn elements.

Errors were divided in two main types: dimensional and logical. Dimensional error was defined as the difference between estimated and true element length expressed as a percentage. The average dimensional errors and the time consumption for the members in the two test groups are displayed in figs. A.7 and A.8.

A test person's dimensional error can be analyzed in two respects: mean error and standard deviation. The mean error is the average difference between the estimated and the true element length expressed as a percentage. Thus, constant over- or underestimation of element length will lead to high mean error values. Making the same number of over- and underestimations will, on the other hand, lead to low mean errors. The standard deviation expresses the consistency of the mean error. A low standard deviation together with a large mean error indicates that the test person made a consistent scaling error.

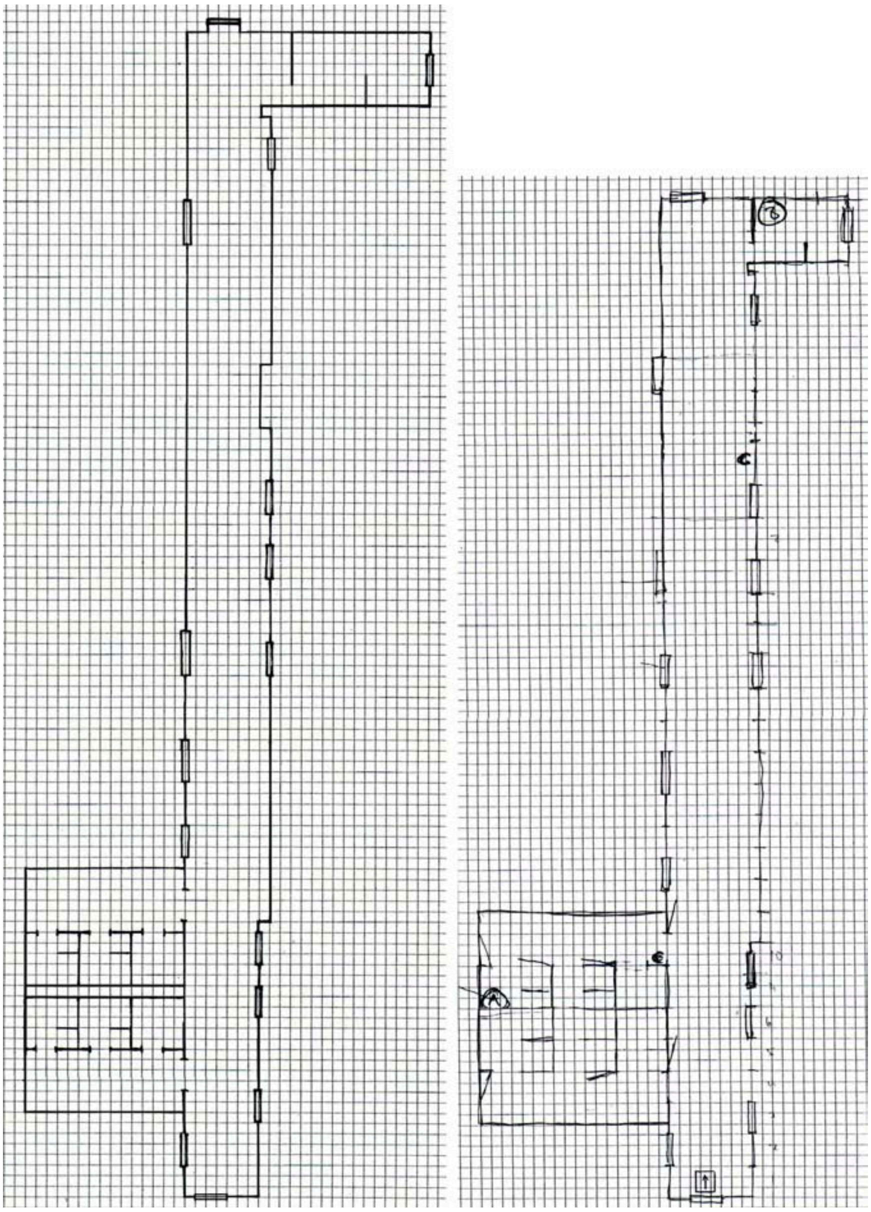

Figure A.4. To the left, the true version of the discretized map. To the right the map of robot operator 1. The starting point was at the lower end.

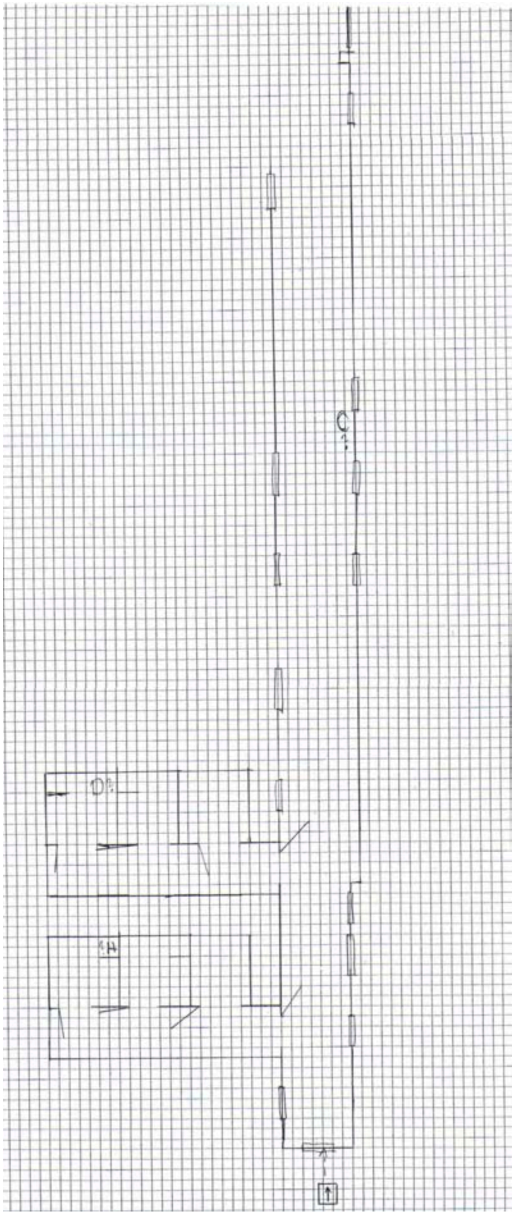

Figure A.5. The map produced by robot operator 3. The orientation of the upper of the two dressing rooms is mirrored and contains an inconsistent door (closed door between the corridor and the upper dressing room). The upper part of the test track was not depicted due to shortage of time.

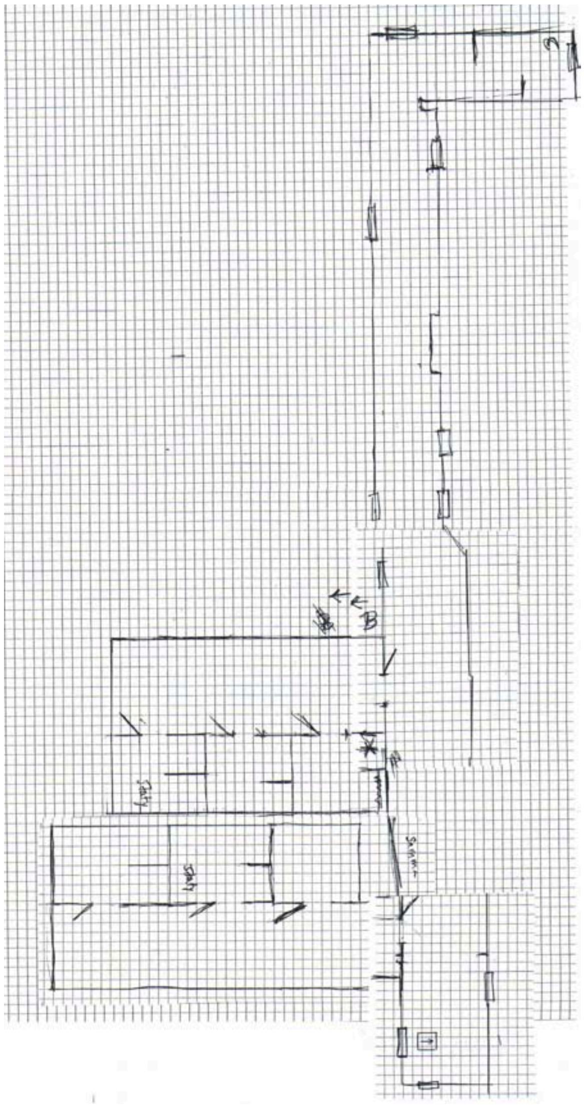

Figure A.6. The map produced by robot operator 10. This operator did not realize that the two dressing rooms were of the same dimensions. Numerous features are missing.

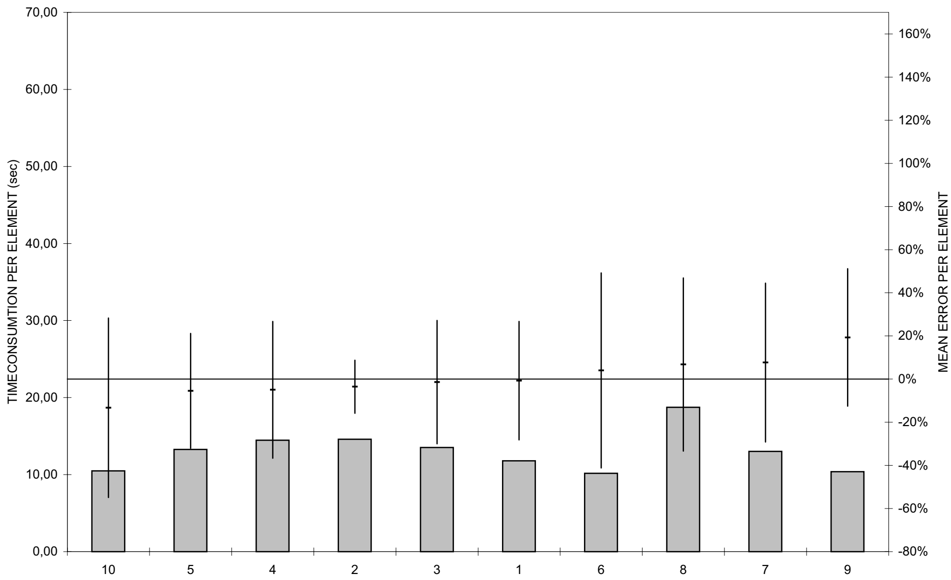

Figure A.7. Mean time consumption per element (bars) and mean error per element (points with std.dev.) for the 10 non-robot users. Sorted left to right according to mean error.

The logical errors were grouped into five sub-types:

1. Missing: Elements missing, for example a missing wall.
2. Added: Elements drawn but not existing in reality.
3. Unexplored: Elements not explored due to misinterpretation of the spatial layout. Only one logical error was given for each neglected area, since it was based on one mistake, although it may have caused several more elements to be missing.
4. Misshapen: Elements with wrong shape for example an element indicating the corridor narrowing instead of widening.
5. Inconsistent: Elements whose depictions do not prove consistent from one view to another. For example, a door existing only from one side of a wall.

All logical errors were given a value of one and they were considered compatible enough to be added together in a sum for analysis. The mentioned performance measures (time consumption, error rate, dimensional mean error, dimensional standard deviation and logical error) were also compiled into an overall performance ranking. The overall ranking was determined by ranking all the participants against

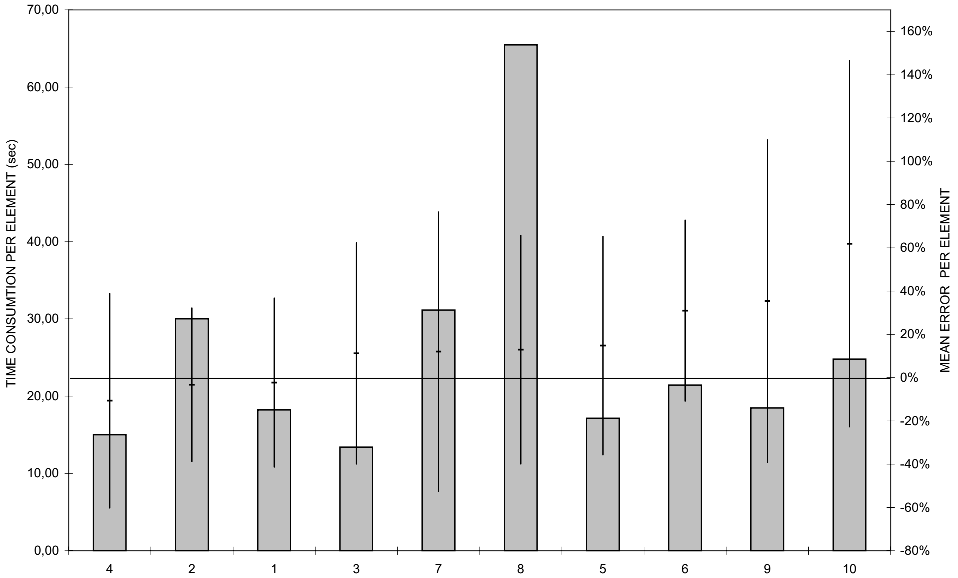

Figure A.8. Mean time consumption per element (bars) and mean error per element (points with std.dev.) for the 10 robot users. Sorted left to right according to mean error.

each other for the five performance measurements and then adding up the individual ranks to give an overall rank.

Time Consumption

The average time consumption for the robot users and the non-robot users is displayed in fig. A.9 (fig. A.9 displays the average of the time values in the form of as bars in figs. A.7 and A.8). On average the non-robot users spent 13 seconds per element while the robot users spent 26. A Students t-Test (one tail, two-sample unequal variance) gives the discovered difference between the groups a 98.5% confidence, i.e. statistically significant.

Although the robot-using group took twice as long, it is clear from the high standard deviation and the individual data in fig. A.8 that some of the robot operators performed as well as some of the non-robot users. This indicates a potential for improvement depending on factors such as training, talent, motivation, fatigue and experience from fields containing similar mental processing.

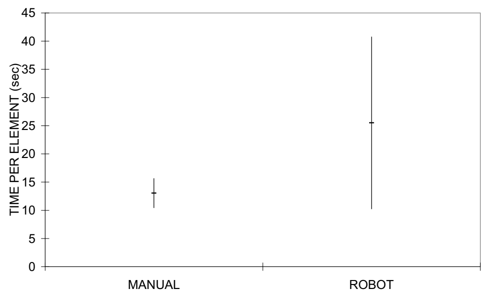

Figure A.9. Average time consumption and standard deviation per depicted element for the non-robot users (MANUAL) and the robot users (ROBOT).

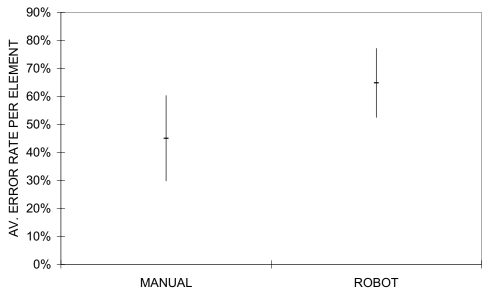

Figure A.10. Average error rate in percentages and standard deviation the non-robot users (MANUAL) and the robot users (ROBOT).

Error Rate

The mean error rate for the two groups, calculated as the percentage of elements with a dimensional or logical error, is displayed in fig. A.10. The experiment showed that the non-robot users had an error percentage of 45% while the robot users had an error percentage of 65%. The two groups had approximately the same standard deviation: 15 for the non-robot users and 12 for the robot users, which indicates a consistent difference in error rate between the two groups. The Student t-Test (one tail, two-sample unequal variance) rates the result as highly significant, 99.7%.

Dimensional Error

As displayed in fig. A.11, the non-robot users on average had a mean error of 1% while the robot users on average had a mean error of 16% (fig. A.11 displays the average of the mean error values displayed in figs. A.7 and A.8). Hence, the robot operators tended to overestimate dimensions while the non-robot users made approximately as many over- as under estimations. Again, the larger standard deviation within the robot-using group implies a potential for improvements such as

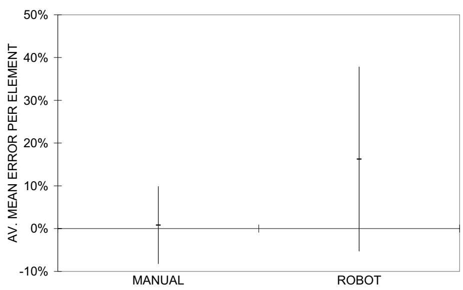

Figure A.11. Average dimensional mean error as a percentage per element for the non-robot users (MANUAL) and the robot users (ROBOT).

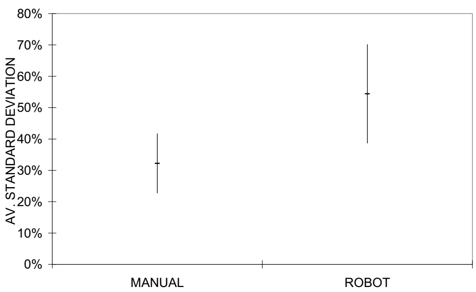

Figure A.12. Average standard deviation of the dimensional mean error for the non-robot users (MANUAL) and the robot users (ROBOT).

suggested for time consumption. The Student t-test rates the result to be significant with 97.1% confidence (one tail, two-sample unequal variance).

The average standard deviation for the two groups, expressing the consistency of the mean error, is displayed in fig. A.12 (fig. A.12 displays the average of the standard deviations displayed in figs. A.7 and A.8). The non-robot group had a mean standard deviation of 32% while the robot group's corresponding value was 54%. In this case the standard deviation values (see fig. A.12) do not differ significantly, 10 for the non-robot users and 16 for the robot users. This indicates a consistent difference between the two groups; the robot users seem prone to having a greater variation in their dimensional estimations. The Student t-Test states this result to be very highly significant, 99.9% (one tail, two-sample unequal variance).

Logical Error

During the test the robot-using group made on average logical errors 4% of the time when depicting an element, fig. A.13. The most common logical errors were to miss or misinterpret elements. The non-robot users only made one type of logical

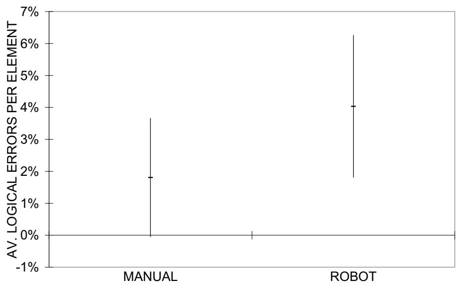

Figure A.13. Average logical errors and standard deviation per element for the non-robot users (MANUAL) and the robot users (ROBOT).

error – they missed depicting 1.8% of the objects. The standard deviations are alike for the two groups: 1.9 for the non-robot group and 2.2 for the robot group. This again implies that there is a significant difference between the two groups regarding logical errors, which is also supported by the 98.7% confidence calculated by the Student t-Test (one tail, two-sample unequal variance).

Overall Ranking

The rankings for the five performance criteria displayed in fig. A.14, show that the robot users are generally over-represented at the lower end compared with the non-robot users. The robot operators occasionally manage to compete with the non-robot users as in the case of dimensional mean error. However, the non-robot operators predominate the total rank. According to the questionnaires the two best robot operators were both highly experienced in the interpretation of 3-dimensional computer representations.

ROBOT 1: Male, 37 years, an industrial designer and product developer, professional 3D-CAD-user, daily computer user with medium skill, seldom or never plays computer games, has tried to operate RC-crafts a few times, inexperienced with joystick control, inexperienced with robot operation.

ROBOT 2: Female, 29 years, M.Sc. in Ergonomic Design and Production, professional 3D-CAD-user, daily computer user with medium skill, seldom or never plays computer games, has tried to operate RC-crafts a few times, inexperienced with joystick control, inexperienced with robot operation.

A.3 Discussion

There are a number of factors to consider when analyzing a person's robot aided exploration of a building. The most interesting factors will vary with the purpose of the mission. In some cases it may be most important to search for certain objects. In other cases it may be of great interest to find a passage through a building and

TIME CONSUMTION	ERROR RATE	DIMENSIONAL DIFFERENCE	DIMENSIONAL STANDARD DEVIATION	LOGICAL ERROR	TOTAL RANK
MANUAL 6	MANUAL 2	MANUAL 1	MANUAL 2	MANUAL 1	MANUAL 1
MANUAL 9	MANUAL 1	MANUAL 3	MANUAL 5	MANUAL 4	MANUAL 2
MANUAL 10	MANUAL 5	ROBOT 1	MANUAL 1	MANUAL 8	MANUAL 3
MANUAL 1	MANUAL 3	ROBOT 2	MANUAL 3	MANUAL 6	MANUAL 4
MANUAL 7	ROBOT 2	MANUAL 2	MANUAL 4	ROBOT 5	MANUAL 5
MANUAL 5	MANUAL 4	MANUAL 6	MANUAL 9	ROBOT 6	MANUAL 6
ROBOT 3	MANUAL 7	MANUAL 4	ROBOT 2	MANUAL 2	MANUAL 7
MANUAL 3	ROBOT 1	MANUAL 5	MANUAL 7	MANUAL 3	ROBOT 1
MANUAL 4	ROBOT 3	MANUAL 8	ROBOT 1	ROBOT 1	MANUAL 8
MANUAL 2	MANUAL 6	MANUAL 7	MANUAL 8	MANUAL 7	ROBOT 2
ROBOT 4	MANUAL 10	ROBOT 4	MANUAL 10	MANUAL 5	MANUAL 9
ROBOT 5	MANUAL 8	ROBOT 3	ROBOT 6	MANUAL 9	MANUAL 10
ROBOT 1	ROBOT 4	ROBOT 7	MANUAL 6	ROBOT 4	ROBOT 3
ROBOT 9	MANUAL 9	ROBOT 8	ROBOT 4	ROBOT 3	ROBOT 4
MANUAL 8	ROBOT 8	MANUAL 10	ROBOT 5	MANUAL 10	ROBOT 5
ROBOT 6	ROBOT 7	ROBOT 5	ROBOT 3	ROBOT 2	ROBOT 6
ROBOT 10	ROBOT 5	MANUAL 9	ROBOT 8	ROBOT 7	ROBOT 7
ROBOT 2	ROBOT 6	ROBOT 6	ROBOT 7	ROBOT 9	ROBOT 8
ROBOT 7	ROBOT 9	ROBOT 9	ROBOT 9	ROBOT 10	ROBOT 9
ROBOT 8	ROBOT 10	ROBOT 10	ROBOT 10	ROBOT 8	ROBOT 10

Figure A.14. All participants ordered according to rank in the different performance criteria and for the total rank. With the best performers listed at the Top. The non-robot users are named manual 1-10. The robot users are named robot 1-10 and shaded.

in yet another, the purpose may be to cover an as large area as possible. Similarly, the impact from different types of errors may vary between missions. For example, in some cases it may not matter if the dimensions are accurate as long as the logical description is correct. No matter the purpose of the mission it will be of interest to carry out navigation to some extent which includes creating a mental model of the spatial layout. In this experiment the operators were forced to draw a map during exploration which in itself is a violation of the spontaneous way the operator may have approached the task in a real case. It is reasonable to believe that the drawing process made the exploration more time consuming. Further, the requirement to draw a map probably improved the accuracy of the spatial mental model since it forced the operator to mentally process the acquired information. The map was probably also a significant memory aid for the test persons during exploration. The restriction to cross-ruled paper may have influenced the test persons to be more structured in their map drawing. The cross-rules also prevented depiction of any curved shapes (there were no curved walls in the explored region). Field tests indicate that robot operators have more trouble with curved than with straight walls.

The robot imposes a number of perceptual disadvantages on the operator. The wide-angle lens makes driving easier but it also distorts the perspective, which makes recognizing objects and judging dimensions harder. The resolution of 240*320 pixels is significantly lower than the resolution of the human eye. Having the camera placed at floor-level gives an unusual perspective and obstacles also easily block it. In addition to drawbacks in visual feedback the robot also lacks inertial and motory information about movements. It is likely that data from sensors measuring roll, pitch, heading and distance, displayed in an easily graspable way, for example overlaid on the video picture as in cockpits, could compensate for lack of motory information.

Despite the mentioned disadvantages, the operation of the robot system did not prove too difficult for the test persons. Despite only limited training, they managed to get around with a reasonable number of collisions (mainly when passing through doorways). The non-robot users did not move at a much faster pace than the robot during the exploration, and most of the time was spent viewing and drawing.

Regarding analysis, it is not obvious in what way the different performance criteria should be evaluated against each other. As mentioned, it will largely depend on the purpose of the mission. The chosen evaluation strategy emphasizes dimensional errors related to small elements (gives a higher error percentage). Further the logical errors were all valuated the same although their consequence may vary depending on mission.

The general validity of results gained is influenced can be categorized according to:

1. Operator – The test participants were arbitrary chosen novices. Training, talent, motivation, fatigue and skills in fields containing similar mental processing are probable to have influence on the operator's performance. The performances by the better robot operators indicate a potential for general improvement.

2. Environment – The experiment was executed in a fairly simple and uncluttered environment with good light conditions of a type familiar to the test persons. It is known that there is a strong relation between environmental complexities and the prospect of gaining SA. Cluttered environments and absence of familiar objects that provide reference complicate matters.

3. Robot – The robot used during the experiment had a minimum of features. Interface design, camera performance and placement, maneuverability, user interface design as well as integration of other sensors influence the system efficiency.

Bearing these in mind the results from the experiment can be used as a guideline for the performance of other users, environments, and robots.

Abbreviations

APC	Armored Personnel Carriers
ATRV	All Terrain Robot Vehicle
CBRN	Chemical Biological Radiological Nuclear
COTS	Components Of The Shelf
DARPA	Defense Advanced Research Projects Agency (United States)
DFWES	Direct Fire Weapon Effects Simulator
DOF	Degrees Of Freedom
EOD	Explosive Ordnance Disposal
FHS	National Defence College
FMV	Defence Materiel Administration
GUI	Graphical User Interface
IED	Improvised Explosive Device
IR	Infra Red
KTH	Royal Institute of Technology
LG	Royal Life Guards
MOUT	Military Operation in Urban Terrain
OCU	Operator Control Unit
PDA	Personal Digital Assistant (handheld computer)
SA	Situational Awareness
SLAM	Simultaneous Localization And Mapping
SWAT	Special Weapons And Tactics
SWEDEC	Swedish EOD and Demining Center
TFT	Thin Film Transistor Liquid Crystal Display
UGV	Unmanned Ground Vehicle
UAV	Unmanned Arial Vehicle
USAR	Urban Search And Rescue
WiFi	Wireless Fidelity (Wireless computer network based on IEEE 802.11 standards)

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