Towards a Unified Behavior Trees Framework for Robot Control

Alejandro Marzinotto, Michele Colledanchise, Christian Smith, and Petter Ögren

Abstract—This paper presents a unified framework for Behavior Trees (BTs), a plan representation and execution tool. The available literature lacks the consistency and mathematical rigor required for robotic and control applications. Therefore, we approach this problem in two steps: first, reviewing the most popular BT literature exposing the aforementioned issues; second, describing our unified BT framework along with equivalence notions between BTs and Controlled Hybrid Dynamical Systems (CHDSs). This paper improves on the existing state of the art as it describes BTs in a more accurate and compact way, while providing insight about their actual representation capabilities. Lastly, we demonstrate the applicability of our framework to real systems scheduling open-loop actions in a grasping mission that involves a NAO robot and our BT library.

I. INTRODUCTION

Behavior Trees (BTs) are plan representation tools commonly used in scenarios where there is no need to have a mathematical foundation encompassing continuous-time dynamics. However, such requirement arises in order to use BTs on more complex applications, e.g. real robots, control systems. This indicates the need to formalize BTs in a mathematical framework that is both accurate and compact.

Intuitively, we measure accuracy to be inversely proportional to the degree of misinterpretation that a certain statement can be subjected to. Likewise, we measure compactness to be inversely proportional to the amount of definitions required to fully specify an idea. Using these two indicators we created a framework that surpasses the state of the art.

In pursuit of the accuracy, we formulated the Action and Condition subsets which remove the ambiguities that could arise when referring to the node Success, Running, or Failure. It is relying on these subsets that we could motivate the node extensions, and compare BTs with other plan representations.

There exist ad-hoc engineering solutions to circumvent the intrinsic limitations of BTs regarding two aspects: nodes are memory-less [5] (do not store the last running node), and BTs execute independently from one another [2] (cooperative tasks are not possible). This paper formalizes and motivates solutions to both problems in an accurate and compact way.

After [13], there is still uncertainty regarding the potential of BTs as a suitable representation to replace Controlled Hybrid Dynamical Systems (CHDSs) [15]–[17]. We address the problem in two complementary ways: from CHDSs to BTs, and vice-versa. This provides important insight about which tasks are representable, under what constraints, and what are the advantages / disadvantages of each paradigm.

As represented in Fig. 1, the BTs and CHDSs belong to the Middle Layer which provides a mechanism for switching between low-level controllers. The Top Layer automatically generates and updates plans, whereas the Bottom Layer handles low-level controllers that interact with the hardware.

To demonstrate the usability of our work, we implemented an open source BT library for the Robot Operating System (ROS) [18], which allowed us to test the concepts described in this paper on real robotic platforms. We briefly analyze the implementation limitations regarding the different ways of resolving subset intersection (prevalence and hysteresis). The main contributions of this paper are listed below:

1) A more accurate and compact BT framework.
2) Introduction of the Action and Condition subsets.
3) Formalization and motivation of two node extensions.
4) Equivalence notions between BTs and CHDSs.

The execution of the task described in Section IX is presented in a video¹, and the source code of the library is publicly available on www.github.com/almc.

The paper is structured as follows: in Section II we review related work, in Section III we formalize BTs and introduce the subsets, in Sections IV and V we present the Node* and the Decorator* extensions, in Section VI we present a formal definition of CHDSs, in Section VII we study the equivalence between BTs and CHDSs, in Section VIII we present the software structure of our implementation, in Section IX we describe the experimental framework, and in Section X we present the conclusions and future work.

¹YouTube video name: Behavior Trees - NAO Grasping [ROS / C++].
II. RELATED WORK

Most of the current BT research efforts are focused towards finding new efficient ways to implement Artificial Intelligence (AI) for entertainment systems, e.g. specifying Non-Player Characters (NPCs) in video-games. This situation often yields BT frameworks that are game-oriented; even though they contain interesting features, they are not generalizable to be used in other research fields, e.g. robotics.

Fortunately, not all papers suffer from these problems but they do differ in several aspects (§1–§11). The criteria, by which these papers were evaluated, is specified in Table I, whereas the comparison itself is presented in Table II. We refrain from expanding on the contributions of each paper, even though they do contain noteworthy contributions, since our primary goal is to point out the differences between them as a mean to justify the need for an unified BT framework.

TABLE I. Criteria used to compare BT publications (§1–§11).

<table>
<thead>
<tr>
<th>Ref</th>
<th>§1</th>
<th>§2</th>
<th>§3</th>
<th>§4</th>
<th>§5</th>
<th>§6</th>
<th>§7</th>
<th>§8</th>
<th>§9</th>
<th>§10</th>
<th>§11</th>
</tr>
</thead>
<tbody>
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<td>[1]</td>
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<td>[3]</td>
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<tr>
<td>[5]</td>
<td>X</td>
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<td>X</td>
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<tr>
<td>[10]</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>[12]</td>
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<td>X</td>
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<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Table II demonstrates that many papers disagree in crucial aspects such as §2, §3, §10, and §11. Our framework, which builds upon [13], [19] and [20], manages to combine every aspect considered in Table I except planning integration. To the best of our knowledge, this is the first paper to achieve such integration. The reader should be aware that BTs are, however, not the only alternative for Middle Layer representation, see [21]–[25]. Lastly, we point out that BTs have also been formalized through CSP semantics in [26].

TABLE II. Comparison of BT publications. [□]: reference to this paper.

III. BEHAVIOR TREES

This section gives a formal description of BTs following the guidelines of [3], [8], [13]. A BT is defined as a directed acyclic graph $G(V, E)$ with $|V|$ nodes and $|E|$ edges. We call the outgoing node of a connected pair the parent, and the incoming node the child. We call the child-less nodes leaves, and the unique parent-less node Root. Each node in a BT, with the exception of the Root, is one of six possible types: four non-leaf (control-flow) node types (Selector, Sequence, Parallel and Decorator), and two leaf (execution) node types (Action and Condition). These are summarized in Table III.

Unlike traditional graph theory trees [14], any node in the BT (except the Root and its only child) can have multiple parents [3]. This allows sub-trees to be reused without having to copy them but decreases readability; for this reason we explicitly advocate for the following workaround: nodes having multiple parents are prohibited, the re-usability of sub-trees is not to be done at the level of control-flow nodes, preferably, it is to be done at the level of execution nodes.

The Root periodically, with frequency $f_{\text{tick}}$, generates an enabling signal called tick, which is propagated through the branches according to the algorithm defined for each node. When the tick reaches a leaf node, it executes one cycle of the Action or Condition. Actions can alter the system configuration, returning one of three possible state values: Success, Failure, or Running. Conditions cannot alter the system configuration, returning one of two possible state values: Success, or Failure. This returned state is then propagated back and forth through the tree, possibly triggering other leaf nodes with their own return states, until finally one of these states reaches the Root. The nodes which are not ticked are set to a special node state: NotTicked. The BT then waits before sending the new tick to maintain $f_{\text{tick}}$ constant. We remark that in the implementation the tick frequency $f_{\text{tick}}$ is completely unrelated to the controller’s frequency $f_{\text{control}}$: they work asynchronously as explained in Section VIII-B.

A. Node Types

The node types behave according to Algorithms 1–11, where the statement $\text{Tick}(\text{child}(i))$: triggers the algorithm that corresponds to its child node type. The execution begins and ends on Algorithm 4, the symbols $S, F, R \subseteq X$, $X(t) \in X$, $U(t) \in U$ are the Success/Failure/Running subsets, state space, and control signals respectively. For a detailed real-life example using these variables refer to Section III-B.

TABLE III. The seven node types of a BT. Ch ≡ children, S ≡ succeeded, F ≡ failed, R ≡ running, N ≡ # children, S, F ∈ N are node parameters.

<table>
<thead>
<tr>
<th>Node Type</th>
<th>Symb.</th>
<th>Succeeds if</th>
<th>Fails if</th>
<th>Runs if</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root</td>
<td></td>
<td>tree S</td>
<td>tree R</td>
<td></td>
</tr>
<tr>
<td>Selector</td>
<td>?</td>
<td>1 Ch S</td>
<td>N Ch F</td>
<td>1 Ch R</td>
</tr>
<tr>
<td>Sequence</td>
<td>→</td>
<td>N Ch S</td>
<td>1 Ch F</td>
<td>1 Ch R</td>
</tr>
<tr>
<td>Parallel</td>
<td>⊑</td>
<td>≥ S Ch S</td>
<td>≥ F Ch F</td>
<td>otherwise</td>
</tr>
<tr>
<td>Decorator</td>
<td>⊗</td>
<td>varies</td>
<td>varies</td>
<td></td>
</tr>
<tr>
<td>Action n</td>
<td>□</td>
<td>$X_n(t) \in S_n$</td>
<td>$X_n(t) \in F_n$</td>
<td>$X_n(t) \in R_n$</td>
</tr>
<tr>
<td>Condition</td>
<td>○</td>
<td>$X_n(t) \in S_n$</td>
<td>$X_n(t) \in F_n$</td>
<td>never</td>
</tr>
</tbody>
</table>
Selector. When a Selector node is enabled, it ticks its children sequentially as long as they continue to return Failure, and until one of them returns Running or Success. If the Selector node does not find a running or succeeding child, it returns Failure, otherwise it returns Running or Success depending on the state of its first non-failing child.

Sequence. When a Sequence node is enabled, it ticks its children sequentially as long as they continue to return Success, and until one of them returns Running or Failure. If the Sequence node does not find a running or failing child, it returns Success, otherwise it returns Running or Failure depending on the state of its first non-succeeding child.

Parallel. When a Parallel node is enabled, it ticks all its children sequentially. If the number of succeeding children is $\geq S$, it returns Success. If the number of failing children is $\geq F$, it returns Failure. Otherwise, it returns Running.

Decorator. When a Decorator node is enabled, it checks a condition on its internal variables, based on which it could tick or not its only child. It applies functions $\phi_1$ or $\phi_2$ to determine the return state, see Algorithm 11 for the template.

Action. When an Action node, indexed $n$, is enabled, it determines the state value to be returned by checking if its current state space configuration $X_n(t)$ belongs to the Success $S_n$, Failure $F_n$ or Running $R_n$ subsets. On the third case, it also performs a discrete control step $\gamma_n : X_n \rightarrow U_n$.

Condition. When a Condition node is enabled, it behaves like the Action, without the Running subset and control step.

Algorithm 1: Selector

```
for i ← 1 to N do
  state ← Tick(child(i))
  if state = Running then
    return Running
  if state = Success then
    return Success
end
return Failure
```

Algorithm 2: Sequence

```
for i ← 1 to N do
  state ← Tick(child(i))
  if state = Running then
    state ← Tick(child(i))
  if state = Running then
    return Running
  if state = Failure then
    return Failure
end
return Success
```

Algorithm 3: Parallel

```
for i ← 1 to N do
  state_i ← Tick(child(i))
end
if nSucc(state) ≥ S then
  return Success
if nFail(state) ≥ F then
  return Failure
else
  return Running
```

Algorithm 4: Main Loop

```
initialize(agent)
BT.parse(agent)
while (active = true) do
  state ← Tick(Root)
  sleep(1/ftick)
end
BT.delete(agent)
return 0
```

Algorithm 5: Action

```
if $X_n(t) \in S_n$ then
  return Success
if $X_n(t) \in F_n$ then
  return Failure
if $X_n(t) \in R_n$ then
  $U_n(t) \leftarrow \gamma_n(X_n(t))$
end
return Running
```

Algorithm 6: Condition

```
if $X_n(t) \in S_n$ then
  return Success
if $X_n(t) \in F_n$ then
  return Failure
```

Algorithm 7: Root

```
return Tick(child(0))
```

B. Action Subsets

Action nodes rely on three subsets: $\{S_n, F_n, R_n\}$, used in Algorithm 5. Condition nodes rely on two subsets: $\{S_n, F_n\}$, used in Algorithm 6. We focus on the Action since the Condition is simpler. These subsets partition the Action’s state space $X_n$, where $X_n(t)$ takes its values, such that the following properties hold for Action $n$ and Condition $n$ respectively: $S_n \cup F_n \cup R_n \supseteq X_n$, and $S_n \cup F_n \supseteq X_n$. We could be more restrictive, i.e. $S_n \cap F_n = R_n = F_n \cap R_n = \emptyset$. However, intersecting subsets allow the use of hysteresis, e.g. the threshold for switching from $R_n$ to $S_n$ is not necessarily the same as the threshold for switching from $S_n$ to $R_n$.

As an example consider the modular driving BT shown in Fig. 2, with the corresponding Action subsets portrayed in Fig. 3. A BT being modular means that it can be treated as a stand-alone Action by BTs of higher hierarchy seamlessly. Modularity is enforced through the logic of the BT (control-flow node placement and subsets definitions). The Root, purposefully omitted in Fig. 2, is always removed before composing two BTs to avoid having multiple tick sources.

These three Actions, scheduled by the Sequence node, try to maintain a proper distance from the next vehicle using control algorithms $\gamma_n(X_n(t)) = U_n(t)$. Defining the notation $\text{return} \_\text{status}_{\text{action}}(\text{time} \_\text{step})$, we illustrate the use of subsets showing two possible event sequences from the perspective of each driver Action $(e|n|c)$: these correspond to the upper/lower branches, i.e. $(s_1^n \rightarrow s_2^n|s_1^n \rightarrow s_2^n|f_1^n \rightarrow f_2^n)$, and $(s_1^n \rightarrow r_2^n|f_1^n \rightarrow f_2^n|f_1^n \rightarrow f_2^n)$ respectively. Qualitatively, both scenarios start with two control steps ($r_2^n, r_2^n$) executed by Normal Driver. On the upper branch, the execution is handed over to Cruise Driver ($r_2^n, r_2^n$) reaching Success on the fifth control step ($s_3^n$). On the lower branch, the execution is handed over to Emergency Driver to take care of an unexpected situation during two control steps ($s_3^n, r_2^n$).

![A generic autonomous driving behavior, represented using a BT.](image-url)

Fig. 2. A generic autonomous driving behavior, represented using a BT.

![Succeeding (S, green), Failing (F, red), and Running (R, yellow) subsets](image-url)

Fig. 3. Succeeding (S, green), Failing (F, red), and Running (R, yellow) subsets. The dots (blue) represent $X(t) \in X$ for $t = 1/ftick \ldots 7/ftick$. The solid arrows / dashed arrows represent transitions caused by the Action’s controller / system dynamics or other controllers respectively.
IV. The Node* Extension

The BT node algorithms presented so far are insufficient to represent plans where it is necessary to “remember” if an Action/Condition sub-tree has already succeeds or failed.

A. Node* Motivation

Let us consider a Sequence node with two fully-actuated\(^2\) Actions whose subsets, \(X_1\) and \(X_2\), are represented in Fig. 4. Under these assumptions, if \(X_1 \cap X_2 \neq \emptyset\) there is at least one variable controlled by both Actions. Depending on the subset definitions, this could yield unsatisfiable BTs, e.g. Action 2 executes \(r_1^{A_2}\), decreasing \(X[1]\) so that \(X(t) \notin S_1\) anymore, Action 1 then executes \(r_2^{A_1}\), \(r_4^{A_1}\); causing an endless cycle.

![Fig. 4. Subsets of two Actions demonstrating how cycles appear.](image)

In general, the traditional BT algorithms have the following limitations: in a Sequence node, for an arbitrary \(j\)-indexed child Action \(A_j\) to be ticked at time \(t_k\) it needs to happen that \(\{X_1(t_k) \in S_1 \cap \ldots \cap X_{j-1}(t_k) \in S_{j-1}\}_{t_k \in R_+}\). Similarly, in a Selector node, for an arbitrary \(j\)-indexed child Action \(A_j\) to be ticked at time \(t_k\) it needs to happen that \(\{X_1(t_k) \in F_1 \cap \ldots \cap X_{j-1}(t_k) \in F_{j-1}\}_{t_k \in R_+}\).

This could be desirable in some cases where we need to guarantee that a certain property holds over a set of Actions, but in other situations it is necessary to “remember” which nodes have already returned Success or Failure, in order to not tick (check) them again on the next iteration. The Parallel node does not have this problem, hence no Parallel* exists.

B. Node* Extended Algorithms

Rather than tracking and storing which children have returned Success or Failure, we use a variable that points to the child that has most recently returned Running. This variable is reset every time the Selector or Sequence returns a terminal state (Success or Failure). See Algorithms 8, 9.

<table>
<thead>
<tr>
<th>Algorithm 8: Selector*</th>
<th>Algorithm 9: Sequence*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 for (i \leftarrow \text{run-index} \to N ) do</td>
<td>1 for (i \leftarrow \text{run-index} \to N ) do</td>
</tr>
<tr>
<td>2 state (\leftarrow \text{Tick(child(i))} )</td>
<td>2 state (\leftarrow \text{Tick(child(i))} )</td>
</tr>
<tr>
<td>3 if state = Running then</td>
<td>3 if state = Running then</td>
</tr>
<tr>
<td>4 run-index (\leftarrow i )</td>
<td>4 run-index (\leftarrow i )</td>
</tr>
<tr>
<td>5 return Running</td>
<td>5 return Running</td>
</tr>
<tr>
<td>6 if state = Success then</td>
<td>6 if state = Success then</td>
</tr>
<tr>
<td>7 run-index (\leftarrow 1 )</td>
<td>7 run-index (\leftarrow 1 )</td>
</tr>
<tr>
<td>8 return Success</td>
<td>8 return Success</td>
</tr>
<tr>
<td>9 end</td>
<td>9 end</td>
</tr>
<tr>
<td>10 run-index (\leftarrow 1 )</td>
<td>10 run-index (\leftarrow 1 )</td>
</tr>
<tr>
<td>11 return Failure</td>
<td>12 return Success</td>
</tr>
</tbody>
</table>

Algorithm 10: Decorator*

The BT node algorithms presented so far are insufficient to represent plans where two or more agents must undertake a common task jointly by synchronizing parts of their BTs.

A. Decorator* Motivation

To control multiple agents using BTs, we have two choices: to have one big BT containing the Actions of all the agents, or to have separated BTs running the Actions of each agent independently from one another. The first solution has the advantage that all the agents can be synchronized inside the same structure, however it is clear that for big groups of agents it turns unmanageable. The second solution has the advantage that BTs are much smaller, easier to understand and expand, however it is not obvious how these independent trees can be synchronized to achieve cooperative behaviors.

We discard the first solution as it is unfeasible for our purposes, focusing on the second scenario which can be dealt with using two approaches. First, making new control-flow nodes with the synchronization capability. Second, making a special Decorator node with the sole purpose of providing its sub-tree with the synchronization capability. We favor the second because it allows the multi-agent features to be kept aside from the execution logic, this permits non-cooperative behaviors to become cooperative by merely placing them under the synchronization Decorator defined below.

B. Decorator* Extended Algorithm

When the Decorator* is enabled, it broadcasts the agent’s name (determined contextually) to the other Decorator* nodes of the same cooperative task, indicating them that it is ready to engage as soon as there are enough agents \(n_{\text{req}}\) to trigger the sub-tree. In most cases, the tick is received by this node when the other agents are busy performing higher priority tasks of their BTs \(n_{\text{now}} < n_{\text{req}}\), in these cases the Decorator* will return without ticking its sub-tree. Eventually, enough agents will be available to engage in the cooperation \(n_{\text{now}} \geq n_{\text{req}}\), at this point the barrier imposed to the ticks by the synchronization Decorator* will be temporarily removed allowing the sub-tree to be executed. Naturally, this requires a software infrastructure, like ROS, capable of handling message passing, and a mechanism that allows each Decorator* to keep track of which and how many agents have broadcasted their messages. Time stamps are used to ensure that such messages were broadcasted recently enough to be valid. See Algorithms 10, 11.

<table>
<thead>
<tr>
<th>Algorithm 10: Decorator*</th>
<th>Algorithm 11: Decorator</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Broadcast(agent, ID)</td>
<td>1 PreFunc(vars)</td>
</tr>
<tr>
<td>2 if (n_{\text{now}} \geq n_{\text{req}}) then</td>
<td>2 if Condition(vars) then</td>
</tr>
<tr>
<td>3 state (\leftarrow \text{Tick(child)})</td>
<td>3 state (\leftarrow \text{Tick(child)})</td>
</tr>
<tr>
<td>4 state (\leftarrow \text{state} )</td>
<td>4 state (\leftarrow \text{phi}(\text{vars}, \text{state}))</td>
</tr>
<tr>
<td>5 else</td>
<td>5 state (\leftarrow \text{phi}(\text{vars}))</td>
</tr>
<tr>
<td>6 Update(agents, (n_{\text{now}}))</td>
<td>6 end</td>
</tr>
<tr>
<td>7 return state</td>
<td>7 PostFunc(vars, state)</td>
</tr>
</tbody>
</table>

\(^{2}\)The function \(\mu : U \to X\) is bijective (one to one correspondence \(\forall u, x\)).

\(^{3}\)The barrier will block again if \(n_{\text{now}} < n_{\text{req}}\) at any point in time.
VI. CONTROLLED HYBRID DYNAMICAL SYSTEMS

Following the definitions of [15]–[17]: a CHDS, shown in Fig. 5, is an indexed collection of Controlled Dynamical Systems (CDS) and a mechanism for switching between them whenever the hybrid state satisfies certain conditions and the control dictates so. More formally, a CHDS is defined as follows: 

\[ \mathcal{H} = (Q, X_0, \mathcal{U}, A_0, \mathcal{E}, \mathcal{I}, \mathcal{Q}, \mathcal{D}, S_0) \in \mathcal{Q} \]

with:

- \( Q \) discrete state space \( Q = \{ q_i | i \in \{1, \ldots, |Q| \} \} \)
- \( X_q \) continuous state space \( X_q = \{ x_{jq} | j \in \{1, \ldots, |X_q| \} \} \)
- \( \mathcal{U}_q \) control signal space \( \mathcal{U}_q = \{ u_{kq} | k \in \{1, \ldots, |\mathcal{U}| \} \} \)
- \( A_q \) edge label set \( A_q = \{ a_{qq} | q \in Q_q \} \)
- \( N_q \) directed neighborhood of \( q (q \in N_q \Rightarrow q \in N_q) \)
- \( \mathcal{E}_q \) edge set, each edge is \( \mathcal{E}_q = (q, \bar{q}, a_{qq}, \mathcal{G}_{qq}, \mathcal{J}_{qq})_{\bar{q} \in N_q} \)
- \( \mathcal{G}_{qq} \) edge label connecting \((q, \bar{q})\) with \(a_{qq} \in A_q\)
- \( \mathcal{J}_{qq} \) state jump sets \( X_q(t) \rightarrow X_{\bar{q}}(t) \in \mathcal{J}_{qq} \subseteq X_q \times X_{\bar{q}} \)
- \( \mathcal{I}_q \) location invariant \( X_q(t) \in \mathcal{I}_q \quad \forall t \in \mathbb{R}, \forall q \in Q \)
- \( \mathcal{C}_q \) control algorithms \( U_q(t) = \Gamma_q(X_q(t)) \)
- \( \mathcal{D}_q \) system dynamics \( X_q(t) = \Delta_q(X_q(t), U_q(t)) \)
- \( \mathcal{S}_t \) initial state \( \{ Q(0), X_q(0), A_q(0), U_q(0) \} \)

Consider a continuous trajectory \((q, \delta_q, X_q(t), U_q(t))\) associated to the discrete state \(q\) with a non-negative time \(\delta_q\) (duration of the continuous trajectory), a piecewise continuous function \(U_q(t) : [0, \delta_q) \rightarrow \mathcal{U}_q\), and a piecewise differentiable function \(X_q(t) : [0, \delta_q) \rightarrow X_q\), such that \(X_q(t) \in \mathcal{I}_q \quad \forall t \in (0, \delta_q)\) and \(\Delta_q(X_q(t), U_q(t)) = X_q(t) \quad \forall t \in (0, \delta_q)\) except for the points of discontinuity.

The trajectory (solution / run) of a CHDS is a (possibly infinite) sequence of continuous trajectories chained together: 

\[ (q^0, \delta_{q^0}, X_{q^0}(t), U_{q^0}(t)) \rightarrow (q^1, \delta_{q^1}, X_{q^1}(t), U_{q^1}(t)) \rightarrow \ldots \]

such that at the event times where transitions occur \(t_0, t_1, \ldots\), defined as: \(t_0 = \delta_{q^0}, t_1 = \delta_{q^0} + \delta_{q^1}, t_2 = \delta_{q^0} + \delta_{q^1} + \delta_{q^2}, \ldots\), the following inclusions hold for the discrete transitions \(a_j\):

\( X_{q^j}(t_j) \in \mathcal{G}_{q^j+1}, q^j \)

\( (X_{q^j}(t_j), X_{q^j+1}(t_j)) \in \mathcal{J}_{q^j+1} \)

for all \(j = 0, 1, \ldots, \infty\). Where \(q^j\) is the \(j\)-th state \(q\) taking place, to which one assigns the symbol \(a_j \equiv a_{q^j+1}\), that represents the jump policy signal at the \(j\)-th state transition.

We show that every CHDS using a specific jump policy can be represented with a BT, and every BT composed only of certain node types can be represented with a CHDS.

A. From CHDSs To BTs

To prove that any CHDS has an equivalent BT it suffices to show that the trajectories both systems produce, when confronted with the same environment (for all possible environments and initial conditions), are identical. Naturally, a CHDS has continuous dynamics which are impossible to mimic using a discrete-time structure like a BT. For this reason, we define a continuous-time BT as a regular BT which has: infinite tick frequency, zero tick propagation time, and zero execution time for Actions and Conditions.

Additionally, assuming that the BT initializes \(Q(t)\) to the initial state of the CHDS, and the CHDS uses a sequential prioritized jump policy \(a_j\). It is straightforward to check that for an infinitesimal time window \(dt\), the BT shown in Fig. 6, in continuous-time, produces the same control as the CHDS shown in Fig. 5. Since this holds true for any infinitesimal time window, it follows that the trajectories are also identical. More complex jump policies are not covered but could possibly be reproduced depending on the case.

Lastly, consider a CHDS where the continuous dynamics are discretized using a finite sampling frequency \(f_{CHDS}\), and a BT which satisfies all the properties of continuous-time BTs except for the tick frequency \(f_{tick}\) which in this case is finite. Under the assumption that \(f_{tick} = f_{tick}\) and following a similar reasoning, it follows that the discretized trajectories are equal because they are sampled / executed synchronously.
B. From BTs To CHDSs

The inclusion of Decorator, Selector\(^*,\) Sequence\(^*\), and Parallel nodes precludes the translation because CHDSs do not support certain features that those nodes bring about. The functionality missing from CHDSs to mimic the Selector\(^*\) and Sequence\(^*\) nodes is being able to rewire (on run-time) the edges between discrete states; this involves dynamic edges. The functionality missing from CHDSs to mimic the Parallel node is being able to execute multiple discrete states simultaneously; this involves multi-valued initial states. Decorators are to be dealt with on a case-by-case basis.

Any BT consisting only of a Root, Selectors, Sequences, Actions, and Conditions has an equivalent CHDS representation. To show the equivalence we write the CHDS version of the BT built using only this set can be represented with a CHDS. The CHDS version of the BT is a sufficient condition to guarantee that any BT built using only this set can be represented with a CHDS.

![CHDS Diagram](diagram.png)

Fig. 7. Selector node with \(N\) Actions / sub-trees represented as a CHDS.

![CHDS Diagram](diagram.png)

Fig. 8. Sequence node with \(N\) Actions / sub-trees represented as a CHDS.

![CHDS Diagram](diagram.png)

Fig. 9. Root node with 1 Action / sub-tree represented as a CHDS.

In these three CHDSs: Fig. 7, Fig. 8, and Fig. 9, the start is to be thought of as an input (where the tick comes from), and the three small colored circles labeled ‘S’, ‘R’, and ‘F’ are to be thought of as outputs (where the tick is returned), none of which are discrete states, they are symbolic and merely used to wire arcs when composing the CHDS of the BT.

Inside the CHDS discrete states, which correspond to BT Actions / sub-trees\(^5\) \((A_1: A_N)\), we place the corresponding controllers \(\gamma_n\) presented in Algorithm 5. From this point it is straightforward to see that under the input / output mindset, the CHDS of a BT node primitive can be embedded as an Action \(A_n\) in a CHDS of higher hierarchy. Performing this procedure recursively turns out to be equivalent to translating the BT to a CHDS starting from the leaves, and following this embedding procedure recursively until the Root is reached.

VIII. ROS IMPLEMENTATION

We propose a ROS implementation of the BT framework, the behavior-trees library, designed abiding by the Google C++ Style Guide with the following compromises:

- **Compatibility** with existing ROS libraries, making it fast and easy to incorporate into new robotic platforms.
- **Simplicity** of the code, allowing other programmers to understand, expand, maintain, and reuse the code.
- **Efficiency** of processing power, providing the complete functionality of BTs, using a low amount of resources.

The implementation consists of three main parts: the Client, where the BT is held, the Server, where the Action and Condition algorithms are held, and the Communication, where the actionlib ROS library provides the connection between the first two. In the following paragraphs we describe how these parts, represented in Fig. 10, work together.

![Client-Server Communication](diagram.png)

Fig. 10. Diagram showing the client-server communication.

A. Client

This part is a ROS module that contains the BT control-flow nodes, and the clients of the Action and Condition nodes, i.e. the BT logic that does not change between applications. It is composed of three parts: Parser, Interface, and Execution.

a) **Parser:** Reads the BT specification from a file and generates the node objects dynamically. The nodes are linked with each other according to the tree structure. The parent only stores a pointer to his first child and refers to the other children using pointers between adjacent brothers.

b) **Interface:** Displays the BT with the node states in real-time using a lightweight OpenGL based interface. It allows the user to navigate through the tree, and override the node states for simulation or debugging purposes.

c) **Execution:** Generates a new tick at the Root of the BT with a fixed frequency. It updates the state of each node by propagating the tick through the branches using the algorithms explained in Section III-A. When the tick reaches a leaf node, an actionlib message is sent to signal the server.

\(^5\)We ignored Conditions because they are simpler versions of Actions.
B. Server

Every leaf node of the BT is linked to a corresponding ROS server module. These contain the functionality of the application’s actuation and sensing algorithms running at the control frequency \( f_{\text{control}} \) referenced earlier. Each server is composed of the three parts: Goal, Publisher, and Execution.

a) Goal: Receives the actionlib messages, that are sent from the client side, each time a tick reaches a leaf node. It updates internal variables, such as the “elapsed time since last message was received”, to determine if the control algorithms should be: started, resumed, or stopped.

b) Publisher: Contains functions to send state updates to the client side, so that the BT node states are kept synchronized with the actual state of the controllers. The user must define the succeeding \( S_n \), failing \( F_n \), and running \( R_n \) subsets for each control algorithm to be implemented.

c) Execution: Runs the main loop of the controller on a separate thread to allow asynchronous actionlib message reception. It periodically checks the “elapsed time since last message was received” in order to destroy the thread if no tick has reached the client node for a certain amount of time.

C. Communication

The client and server parts are connected using actionlib; the most widely used ROS library. It functions under a non-supervised goal achieving scheme, where the client sends a goal to the server and waits for it to either succeed or fail.

Clearly, actionlib does not work with the same paradigm as the BTs, but it provides a valuable framework of client-server communication in ROS. We took advantage of this to provide our behavior-trees library with the set of callbacks that allows it to schedule in time the different nodes of a BT. Among these functions\(^6\) we highlight the following:

- **DoneCB**: called upon goal completion.
- **ActiveCB**: called upon goal acceptance.
- **FeedbackCB**: called upon feedback publishing.
- **GoalCB**: called upon new goal reception.
- **PreemptCB**: called upon goal preemption.
- **ExecuteCB**: called periodically if the node is active.

D. Implementation Limitations

There are two main limitations: the first cannot be avoided due to the nature of BTs, the second has a small workaround:

1) BTs operate by calling a function from inside another function in a recursive manner following the Algorithms 1–11. Computationally, this could produce stack overflow for huge trees, even for implementations like ours that separate the control algorithms from the execution logic using clients and servers.

2) For each tick that is sent to traverse the BT, a large number of checks has to be performed over the state spaces of the Actions in the tree. Our implementation overcomes this problem by performing both calculations asynchronously, thereby preferring to get a delayed state update than blocking the tick flow.

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\(^6\)The callbacks DoneCB, ActiveCB, and FeedbackCB belong to the client. The callbacks GoalCB, PreemptCB, and ExecuteCB belong to the server.

IX. System Demonstration

To show the potential of BTs and the usability of our library, we implemented in ROS a grasping task using a NAO humanoid robot from Aldebaran Robotics, see Fig. 12.

A. The Mission

We define a scenario where the robot stands up, walks towards a table, and attempts three different grasps on an object until one of them succeeds or all three fail. If a grasp succeeds: the robot informs the user, releases the object, turns 180 degrees, and returns to the starting position. If all grasps fail, the robot informs the user, but does not return to the starting position. In both cases, whether the grasp was successful or not, the robot sits down and disables its motors.

To improve the safety of the robot behavior, we include fallback handling for motor temperature and falls. This means that at any point in the execution of the program, if the robot detects either of these conditions, it automatically disables the current node and enables the proper one to handle the situation. For instance, if the robot detects a high motor temperature, it sits down and disables the motors in order to prevent overheating. Additionally, if the robot detects a fall, it attempts to stand up before continuing.

B. Behavior Tree Representation

The BT of this task is shown in Fig. 11, and features two characteristics that, in general, make BTs powerful tools:

a) Flexibility: It is easy to extend the behavior by adding or removing nodes without modifying the structure of the tree. For instance, to include detection and proper handling of low battery levels, it suffices to add the dashed Condition in Fig. 11. In contrast, adding or removing a node from a CHDS, could potentially involve wiring \( 2N+1 \) arcs (\( N/N \) arcs going to / departing from the node + 1 self-loop).

b) Modularity: It is possible to encapsulate behaviors as sub-trees, in order to append them to a tree with a higher hierarchy. To do this, the sub-tree to be appended needs to be modular, which informally means it never returns Success or Failure until it has actually finished executing its goal.

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![Fig. 11. BT representation of the grasping task implemented on the NAO. We entirely disregard the automatic plan generation, i.e. Top Layer of Fig. 1.](image-url)
X. Conclusions

We presented an algorithmic BT framework which is substantially more accurate and compact than previous descriptions. We provided equivalence notions between BTs and CHDSs which gave us insight about the advantages of each framework: using BTs we lose the ability to be in a certain state, but we achieve modularity. A BT is modular if its control-flow nodes and the subsets are laid out in such a way that the goal represented succeeds or fails in finite time, and its Root receives Running for all intermediate states.

We introduced the Action and Condition subsets, which allowed us to formalize and motivate two extensions to the basic BT functionality, thereby avoiding the use of ad-hoc solutions. The robotic platform tests and theoretical analysis allowed us to conclude that BTs can replace certain CHDSs without losing accuracy, descriptive power, or human readability. Moreover, BTs have a larger set of representable plans because nodes such as the Parallel, Selector*, or Sequence* do not have a corresponding CHDS representation.

While not explicitly demonstrated here, we believe that the flexibility and modularity of BTs, make them a good candidate for representing Middle Layer plans that are created and maintained automatically by high-level AI algorithms. We acknowledge that the current demonstration merely shows open-loop action scheduling through BTs, and we plan to address this by upgrading the system to encompass closed-loop controllers. Lastly, we plan to analyze the relation between our framework parameters and its functionality.

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