

space) the more flexed the fingers will be. This is due to the fact that the starting position is with fingers and thumb totally extended and the transition between grasp types is smooth. The clusters seem to be elongated in the start-end posture direction. This makes sense, since the whole movement was taken into account when clustering the grasp types.

In the grasp taxonomy of [4] the thumb plays a crucial role in classifying the grasp types. The clusters which were created here tend to go in accordance with this thumb classification, but there are some conflicts. The reason for this could be that the clustering algorithm gives each finger equal importance, while in [4] the thumb plays a prominent role. Some grasp types do not employ all fingers, which means that potentially some fingers are not relevant for the grasp definition. Currently those fingers are taken into account with the same importance as fingers in contact with the object.

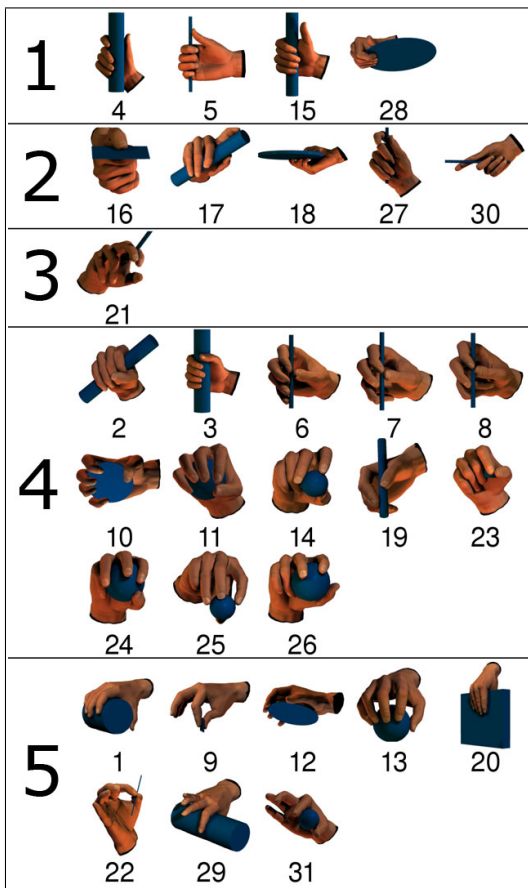


Fig. 5. Clusters of the human grasps.

V. CONCLUSIONS

The goal of the work presented here, differently from all the existing grasp taxonomies, was to model the spatial dimensionality and temporal context of hand actions. Instead of studying how different objects are grasped, we study how different grasps are performed. Apart from the important insights of human hand motion, the developed technique has also been used to evaluate the state-of-the-art taxonomies. We have shown how the technique can be used to embed high

dimensional grasping actions in a lower-dimensional space suitable for modeling, recognition and mapping. Considering the whole grasping sequence instead of just a single grasp posture facilitates the spatial and temporal reconstruction of a grasping action. The method is evaluated on real data.

An immediate application of the extracted latent space is a non-parametric dynamic model of grasping actions for tracking and classification [21]. We do not model dynamics explicitly but include back-constraints that indirectly enforce temporal continuity in the latent space. This avoids the unimodal nature of using an auto-regressive dynamic model. The created GPLVM model potentially allows the generation of concatenated grasping actions with natural transitions. Thus, one idea is to apply constraints in the latent space in a similar way as in [15]. Together with the evaluation in terms of grasp classification this remains our future work.

REFERENCES

- [1] S. Ekvall and D. Kragic, "Grasp recognition for programming by demonstration tasks," in *ICRA*, 2005, pp. 748–753.
- [2] S. Bitzer and S. Vijayakumar, "Latent spaces for dynamic movement primitives," in *Humanoids 2009*, 2009.
- [3] S. Ekvall and D. Kragic, "Interactive grasp learning based on human demonstration," in *ICRA*, 2004, pp. 3519–3524.
- [4] T. Feix, R. Pawlik, H. Schmiedmayer, J. Romero, and D. Kragic, "A comprehensive grasp taxonomy," in *Robotics, Science and Systems: Workshop on Understanding the Human Hand for Advancing Robotic Manipulation*, June 2009.
- [5] R. Urtaun, D. J. Fleet, and P. Fua, "3D people tracking with gaussian process dynamical models," in *CVPR*, 2006, pp. I: 238–245.
- [6] J. S. M. Santello, M. Flanders, "Postural hand synergies for tool use," in *The Journal of Neuroscience*, 1998.
- [7] D. Song, K. Huebner, V. Kyrki, and D. Kragic, "Learning task constraints for robot grasping using graphical models," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2010.
- [8] A. Tsoli and O. C. Jenkins, "Neighborhood denoising for learning high-dimensional grasping manifolds," in *IROS*, 2008, pp. 3680–3685.
- [9] M. T. Ciocarlie, C. Goldfeder, and P. K. Allen, "Dimensionality reduction for hand-independent dexterous robotic grasping," in *IROS*. IEEE, 2007, pp. 3270–3275.
- [10] M. T. Ciocarlie, S. T. Clanton, M. C. Spalding, and P. K. Allen, "Biomimetic grasp planning for cortical control of a robotic hand," in *IROS*. IEEE, 2008, pp. 2271–2276.
- [11] H. B. Amor, G. Heumer, B. Jung, and A. Vitzthum, "Grasp synthesis from low-dimensional probabilistic grasp models," *Journal of Visualization and Computer Animation*, vol. 19, no. 3-4, pp. 445–454, 2008.
- [12] R. Urtaun, D. J. Fleet, A. Geiger, J. Popović, T. J. Darrell, and N. D. Lawrence, "Topologically-constrained latent variable models," in *ICML08*, vol. 307. ACM, 2008, pp. 1080–1087.
- [13] R. Urtaun and T. Darrell, "Discriminative gaussian process latent variable model for classification," in *ICML*, 2007, pp. 927–934.
- [14] S. Bitzer, S. Klanke, and S. Vijayakumar, "Does dimensionality reduction improve the quality of motion interpolation?" in *ESANN09*, no. 5500, pp. 2319–2323, December 2000.
- [15] S. Calinon, F. Guenter, and A. Billard, "On learning, representing and generalizing a task in a humanoid robot," *IEEE Transactions on Systems, Man and Cybernetics, Part B*, vol. 37, pp. 286–298, 2007.
- [16] N. D. Lawrence, "The gaussian process latent variable model," The University of Sheffield, Department of Computer Science., Tech. Rep.
- [17] N. D. Lawrence and J. Quinero-Candela, "Local distance preservation in the gp-lvm through back constraints," in *ICML06*, pp. 513–520.
- [18] J. B. Tenenbaum, V. Silva, and J. C. Langford, "A global geometric framework for nonlinear dimensionality reduction," *Science*, vol. 290, no. 5500, pp. 2319–2323, December 2000.
- [19] S. T. Roweis and L. K. Saul, "Nonlinear dimensionality reduction by locally linear embedding," *Science*, no. 5500, pp. 2323–2326, 2000.
- [20] T. Iberall, G. Bingham, and M. A. Arbib, "Opposition space as a structuring concept for the analysis of skilled hand movements," *Experimental Brain Research Series*, vol. 15, pp. 158–173, 1986.
- [21] J. Romero, H. Kjellström, and D. Kragic, "Hands in action: Real-time 3d reconstruction of hands in interaction with objects," in *ICRA*, 2010.