Controlling a Supernumerary Robotic Finger Exploiting Intrinsic Kinematic Null Space

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Idea

The purpose of this ongoing research is to develop control paradigms that are specifically focused on users and their tasks [1]. The fundamental concept is to capitalize on the human musculoskeletal system's redundancy, i.e. motions of the body that do not affect the action performed by the natural limbs, for controlling extra degrees of freedom.

With this work, the Intrinsic Kinematic Null Space control paradigm is defined and applied to control a wearable Supernumerary Robotic Finger [2].

Intrinsic Kinematic Null Space (IKNS)

Considering the redundancy of the human body with respect to manipulation tasks performed typically by hands, we distinguish between:

- Extrinsic Kinematic Null Space (EKNS).
- Intrinsic Kinematic Null Space (IKNS).

The kinematic null space of joints which are not used in the task belongs to the first category, whereas the IKNS refers only to the null space of involved joints.

Identification of IKNS

Ages, habits, and lifestyles strongly influence how people interact with objects and surroundings, making individuals prone to perform tasks differently. Hence, calculating a-priori the kinematic intrinsic null space on the basis of existing kinematic models would have signified discarding the interindividual variability, which instead is one of the strengths of this approach. A data driven procedure has been developed to overcome this limitation.

Kinematic chain identification

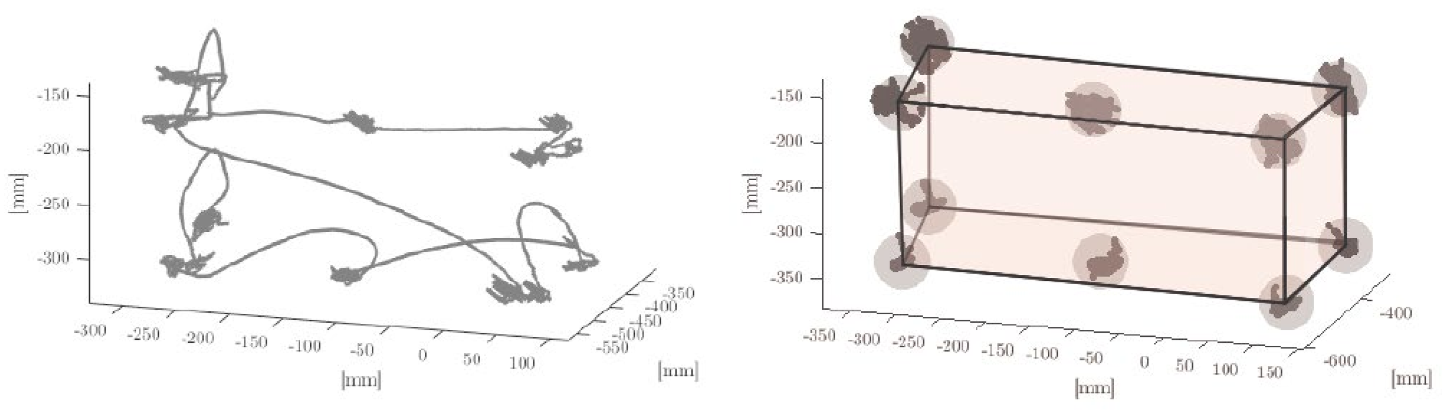
The kinematic chain involved in the task need to be a-priori identified, and this can be done by considering some general knowledge on the kinematic constraints of the human body. For instance, considering a single-arm task, the hand represents the end-effector, and consequently the joints of shoulder, elbow, and wrist, and the associated links, are the significant chain for the IKNS computation.

Joints motion analysis

To project the multidimensional space of the IKNS in the extra degree of freedom (DoF) space (i.e., opening/closing of the Supernumerary Robotic Finger), the acquired values are processed through Principal Component Analysis (PCA) and reduced into a set of values of linearly uncorrelated variables. The direction for controlling the intended DoF is denoted with $z \in R^n$, where n is the cardinality of the IKNS.

Workspace clustering

Since the IKNS of a single-arm manipulation task varies at different positions of the hand, computing the null space (and consequently the PCs) for each point in the arm workspace should be necessary to have a complete IKNS evaluation. We eased the process by computing the null space base in any point of the user's workspace starting from its value in a limited and predefined set of points.



Workspace Interpolation

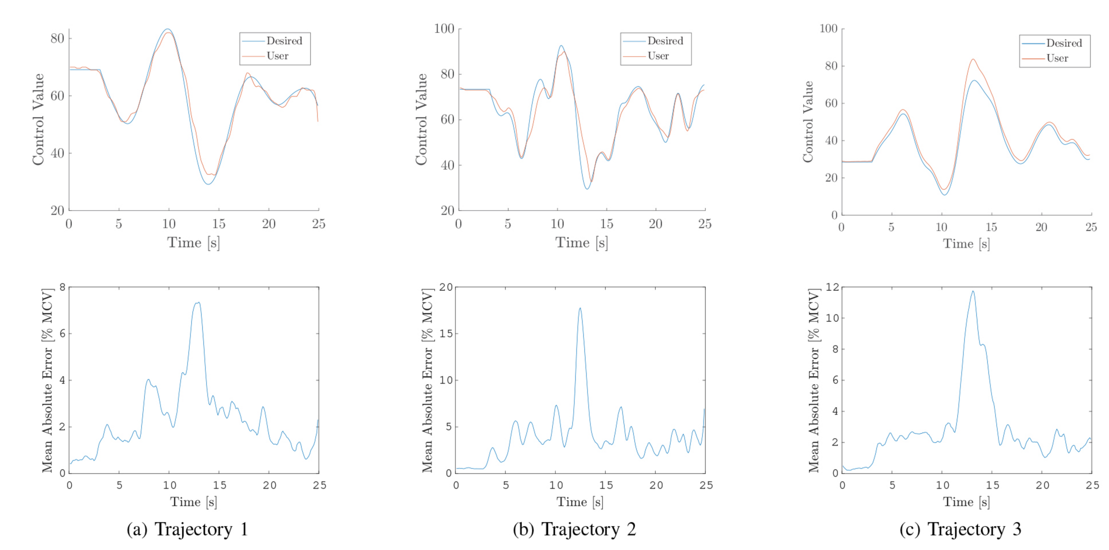
A 3D Delaunay triangulation-based interpolation is used to reconstruct the proper direction z. Thus, the control signal c is calculated as $c = \frac{\hat{z}q - \hat{m}}{|\hat{M} - \hat{m}|}$, where $\hat{z} \in R^n$ is the interpolated direction that projects the current n-dimensional joint vector $\boldsymbol{q}$ into the mono-dimensional space of the DoF, while $\hat{m}$ and $\hat{M}$ result from the interpolation of m and M (minimum and maximum values of the user motion along z), and are used to normalize the control signal in the range from 0 to 1.

Experimental Evaluation

Experiments were conducted both in virtual and in real environments, and designed to meet the final usage of the Supernumerary Robotic Finger in activities of daily living.
Ten subjects (7 males, 3 females) participated to both the experiments.

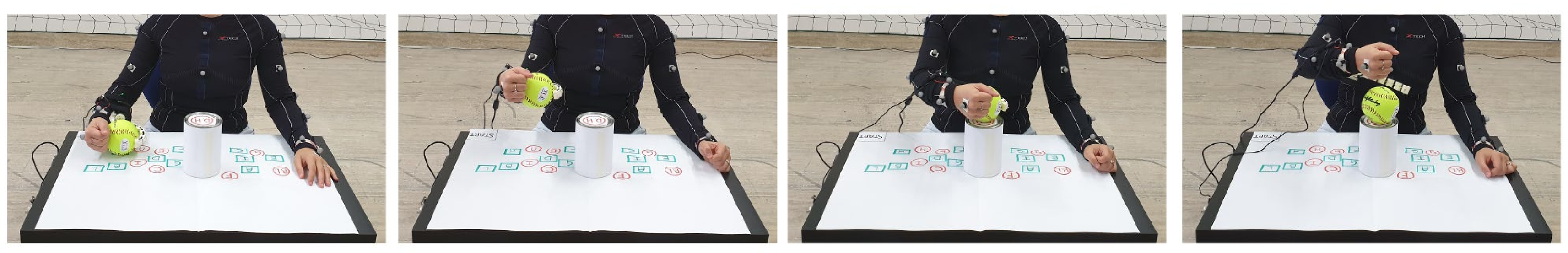
Virtual Environment

Goal: Answering the question: *"Is the generated control signal appropriate for attaining a desired behavior?"*
Procedure: We evaluated the user's accuracy in a tracking task, i.e. in following a predefined reference profile exploiting the proposed control system. This kind of setup was thought to simulate the execution of precise opening/closing movements of the Supernumerary Robotic Finger comparing performance between using the IKNS control and a gamepad.
Metric: Root Mean Square Error (RMSE).
Results: A statistical analysis was conducted to compare results obtained with the two control strategies. A paired-samples t-test revealed that there is no statistically significant difference between the mean RMSEs recorded with the IKNS control and those recorded with the gamepad control.



Real Environment

Goal: Answering the question: *"Is the proposed approach suitable to accomplish common activities of daily living?"*
Procedure: We asked users to perform a pick-and-place task with multiple objects and different target locations. Users wore the Supernumerary Robotic Finger on the right forearm, mimicking a post-stroke hemiparesis, and controlled the opening/closing actuation with the same arm using the IKNS control strategy or a ring-shape switch.
Metrics: Time to accomplish the task and number of successes.
Results: User failed 11 times using the IKNS control, and one time with using the ring switch. Trials in which users failed were removed and not considered in the time analysis. Exact sign test was used to compare the performance differences. Outcomes of the test confirmed that performing the trials using the IKNS control elicited a statistically significant median increase in time compared to the ring modality.



Conclusions

An automatic procedure based on PCA has been proposed to identify, compute, and exploit the IKNS. Results of the experimental campaign demonstrated that the proposed control strategy is suitable for controlling the additional DoF. Although the Intrinsic Kinematic Null Space control has been evaluated for controlling a Supernumerary Robotic Finger, the same strategy can be adopted to cooperate with supernumerary limbs in numerous scenarios (e.g. surgical interventions, handling of loads, etc.). The potential of the proposed approach becomes even more evident in the case of users with disabilities.

[1] S. Gurgone, D. Borzelli, P. De Pasquale, D. J. Berger, T. L. Baldi, N. D'Aurizio, D. Prattichizzo, and A. D'Avella, "Simultaneous control of natural and extra degrees of freedom by isometric force and electromyographic activity in the muscle-to-force null space," Journal of Neural Engineering, vol. 19, no. 1, p. 016004, 2022.
[2] D. Prattichizzo, M. Malvezzi, I. Hussain, and G. Salvietti, "The sixthfinger: a modular extra-finger to enhance human hand capabilities," in Proc. IEEE Int. Symp. in Robot and Human Interactive Communication, Edinburgh, United Kingdom, 2014, pp. 993–998.