Trends in the Design of Control Mappings for Non-Anthropomorphic Appendages

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***Abstract*—When operating robots or robotic wearables of different form or function than the human body, a control scheme needs to be designed to map human motion onto machine motion. Focusing on robots that replace or extend the capabilities of the user's hand, we collected and organized examples of non-anthropomorphic hands (NAHs) in literature, art and industry and organized them by features which affected control scheme design. We report trends found in form and control schemes across the different categories of NAHs, consolidate the metrics most commonly used to evaluate functionality of NAH systems, and begin discussion of a method for developing feasible control schemes for arbitrary robot forms.**

I. Introduction

A human-operated, robotic wearable requires a control scheme to translate the intentions of the user into the action-space of the robot. Because the materials, mechanical properties, and desired task-related capabilities of machines are generally quite different from those of their users, robotic wearables that closely imitate their user's form and motion may not always be desirable. Instead, non-anthropomorphic designs may prove both functional and advantageous for extending a user's capabilities [1]. However, designing control schemes and interfaces to map between different forms and/or action spaces is nontrivial [2] (e.g. Figure 1).

The virtual reality (VR) community has demonstrated functional control mappings between humans and non-anthropomorphic avatars, including avatars with additional appendages and/or degrees of freedom (DOF) [3], [4]. Given that wearables can be simulated in VR without the overhead of physical prototyping, we hypothesize that control schemes and interfaces generated and validated in VR can provide insight on how to design wearable robotic systems in physical reality.

Here we examine current non-anthropomorphic hands (NAHs) in both physical and virtual reality, categorizing them by features that affect their control mappings. A more thorough treatment of the design features of these different categories of NAHs and the possibilities for research transfer between them is given in our recent work [1]. Our aim is to present NAHs as a subject for future research, particularly for developing functional control schemes for novel forms of robots. Other applications for NAH research may include exploring the limitations of the body schema, understanding human motor learning processes, and developing training protocols that effectively scaffold the acquisition of novel motor skills.

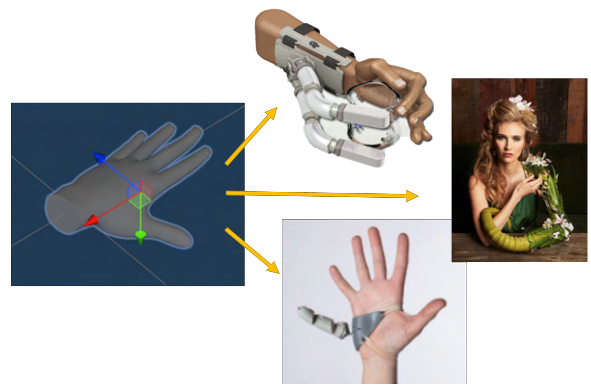

Fig. 1. A hand can control a variety of wearable robot forms—for instance, a grasp-assist device [5], a tentacle prosthesis [6], and a supernumerary digit [7], [8]—given the correct choice of control scheme to map between them.

II. Current Non-Anthropomorphic "Hands" and Their Control Schemes

We conducted a survey of literature involving mappings between human hands and non-anthropomorphic hands, including experiments in both physical and virtual reality [1]. Papers studying "non-anthropomorphism" in the sense of appearance only were excluded; our definition of "non-anthropomorphism" required actual differences in topology or in movement behavior, such that invention of a control scheme would be required in order to function. We noted the following information: the shape and movement space of the non-anthropomorphic device, their associated control schemes and interfaces, the feedback and training protocols that were implemented, and what functionality criteria were used for evaluation.

Our survey revealed a surprising lack of diversity in the shape of non-anthropomorphic devices (see Figure 2). Most "non-anthropomorphic" devices at the hand-level deviate from human hand topology only in the number and length of the fingers [7], [14]–[22]. Substantial topological differences were found more commonly in art or game design [6], [23], although even there, there was heavy reliance on reductive control schemes—for instance, constraining the entire movement space of the robot into a few discrete, task-related movements, or mapping user fingers to robot digits in a one-

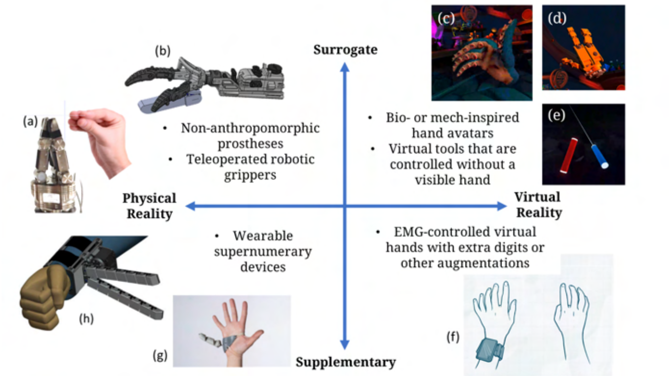

Fig. 2. A chart categorizing NAHs by two features: whether the NAH exists in the real world or in virtual reality, and whether the NAH acts as a surrogate hand or to supplement the user's hand. Wearable NAHs tend to fall in the supplementary category, which requires a control scheme that does not interfere with the user's primary motion—one that goes beyond a one-to-one mapping from user hand to device. Sources: a) [9], b) [10], c) and d) [11], e) [12], f) [13], g) [7], [8], h) [14], [15].

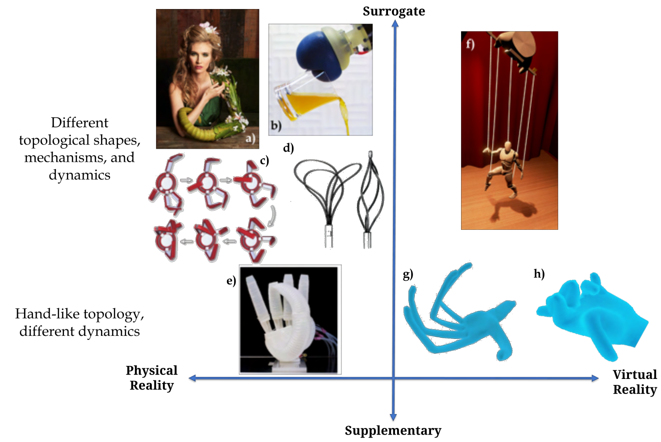

Fig. 3. Examples of potential NAHs that go beyond the "fewer fingers"/"extra fingers" paradigm shown in Figure 2, taken from art and industry. a) [6], b) [25], c) [26], d) [27], e) [28], f) [29], g) [23], h) [23].

to-one fashion while ignoring superfluous digits.

Our survey revealed limitations in the variety of current NAH forms, matching the limited variety of control schemes to support them. Examples of possible NAHs that go beyond the "fewer/extra fingers" paradigm of Figure 2 are shown in Figure 3, and include grippers that do not rely on a fingered topology (e.g. basket grippers, tentacles, or a soft jamming gripper), NAHs for non-grasping tasks, bio-inspired NAHs (such as wings and flippers), and NAHs inspired by mechanical devices or machines (e.g. ones that spin or extend/retract). NAHs can also differ from human hands in movement instead of in shape; for instance, NAH fingers may have joints that bend in unfamiliar directions or have segments that can change length. Control schemes have not been developed for all of these forms; the examples shown in Figure 3 that are manually operated rely on five or fewer buttons or pressure sensors that may or may not be attached to the user's body. We propose a method for identifying feasible control schemes adequate for such devices in the following section.

III. User-Centered Design of Control Schemes for Arbitrary Robot Forms

Our literature review provided metrics for evaluating the success of a control scheme for a non-anthropomorphic robot; however, methods for developing feasible control schemes remain an open question. Nehaniv and Dau [24] describe mathematical methods for measuring correspondence between dissimilar bodies; importantly, they emphasize that the identification of a correspondence is observer-dependent. Is developing a feasible control scheme then user-dependent?

We hypothesize that the correspondences between dissimilar bodies that are identified by different users may share enough commonalities to form the basis of a functional control scheme mapping. Utilizing VR, we intend to portray novel wearable robots on participants' bodies as we expect them to be used. We will ask participants to provide the verbal, hand or body cues that they associate with the avatar's animated motions, or in other words, the commands they would like to use to tell the virtual robot to execute the displayed action. By clustering user inputs, we expect to find physical and motive associations that are common across the majority of users, as well as preferences between different modalities of control input. We then build a control scheme iteratively, leveraging common associations at each step.

The functionality of our NAH system will be evaluated using the metrics collected from our literature review, including both cognitive and objective measures of system performance. Objective measures are evaluated on a task-specific basis; the speed, precision, accuracy, and improvement that a user exhibits at the task over time can inform the functional quality of the control scheme design. Cognitive metrics such as user preference, cognitive workload, presence, and limb ownership are also valuable, particularly in studies on the supplementary half of the NAH chart. This information may provide insight into the mental processes that lead to the system's functional performance.

IV. Conclusion

When operating robots of different form or function than the human body, a control scheme needs to be designed to map human motion onto machine motion. We presented a survey of existing non-anthropomorphic hands, along with their control mappings, evaluation metrics and design constraints. Future work in developing control schemes for arbitrary wearable robot forms may benefit from translating research methods and insights across different categories of non-anthropomorphism, and by leveraging relatively new opportunities afforded through VR platforms to observe and prototype user-defined mappings. We expect the information here to enable future control scheme designs for arbitrary shapes of novel robots, as well as to open avenues for future research into the limits of the body schema and the learning process that underlies the development of novel motor skills.

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