Journal of Mechanical Design

Technical Brief

Design and Virtual Prototyping of Rehabilitation Aids

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This paper presents the methodology for user-customized design of a class of one-of-a-kind assistive devices. This class consists of passive, articulated mechanical manipulation aids, which are physically coupled to the user and therefore, must be customized to the user. Geometric and kinematic measurements of the user are used to create a virtual model of the user. The design of the customized product is based on kinematic synthesis and simulation. An integrated virtual environment, with a virtual model of the user interacting with the product, allows the testing, iterative re-design, and evaluation of the product. Geometric and kinematic data acquisition, mechanism design and analysis, CAD/CAM and visualization modules aid the designer in this process. A head-controlled feeding aid for quadriplegics is used to illustrate the approach.

Introduction

We address the design and virtual prototyping issues related to the customized, one-of-a-kind products that require physical interaction with the human user. Specifically, we focus on a class of rehabilitation assistive devices called teletheses, which are worn or attached to the users. This class of passive articulated mechanical devices, reminiscent of the early mechanical teleoperators, are powered by the user's functional musculature. The considerable variability in the physiological performance across individuals within a population creates the need for designing products that are specific to an individual (Orpwood, 1990). While many criteria of general product design are equally applicable here, it is difficult to apply universal design principles to products that depend on physical contact with humans for their use or operation (Kumar et al., 1996).

There is often a high level of motivation for disabled people to independently perform many of the activities of daily living such as eating (Reswick, 1990). Actively-controlled general purpose robot arms have not been very popular among people with disabilities for tasks involving contact with the user for reasons of reliability, complexity and cost. (Harwin et al., 1995). In contrast, aids like prosthetic limbs controlled by passive proprioceptive feedback with the intimate mechanical contact with the user are found to be more useful (Doubler and Childress, 1984). The Magpie (Evans, 1991) is an example of such a device. It is a four degree-of-freedom telethesis which allows the user to manipulate a feeding utensil controlled by the movements of the leg and the foot. However, the Magpie cannot be used by quadriplegics who are completely paralyzed below the neck. Hence, in the case study presented in this paper the feeding aid is designed to be actuated by the user's head motions.

Customized Product Design

Mass customization models discretize the variability in the population into categories and sizes. Products are then designed to fit statistically "average" people while retaining some flexibility of customization. For instance, rehabilitation devices are built to allow the prosthetist to adjust several kinematic parameters on the manufactured device. This process requires repeated trials and does not guarantee a perfect fit. Individualized customization models rely on measurements of the user and custom-fitting using skilled manual labor leading to longer manufacturing times and higher costs. Current manufacturing methods, including flexible manufacturing technology that targets the specific needs of low volume batch production, do not address the unique challenges underlying the manufacture of individualized one-of-a-kind products in batch sizes of one.

Our approach to individualized product realization emphasizes: (a) the automated, accurate measurement of each individual user and extraction of design specifications from these measurements; (b) customized design to these specifications; (c) simulation, testing and evaluation of the product before and after manufacture; (d) involving and incorporating feedback from the consumers at all stages of the design process.

The remainder of the paper describes the engineering technologies that are required to accomplish these objectives using the example of a feeding device for quadriplegics.

Design Process

The three important stages that are essential for rapid design and prototyping of customized products are outlined below:

User and Task Assessment. The primary goal of this stage is to quantitatively assess the capabilities and the needs of the individual user and build a personalized virtual model of the human user interacting with the environment. We have automated the relevant user data acquisition and extraction of the design specifications, permitting a rapid, detailed and accurate assessment. For example, kinematic motion capture permits us to measure and

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Contributed by the Design Automation Committee for publication in the JOURNAL OF MECHANICAL DESIGN. Manuscript received Dec. 1997; revised May 1999. Associate Technical Editor: B. Ravani.

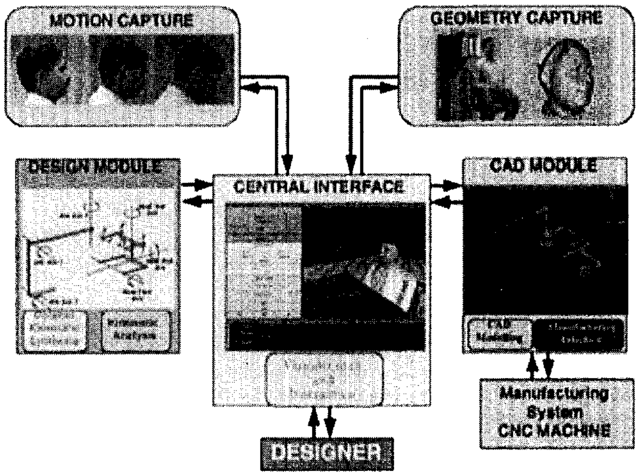

Fig. 1 Integrated design environment

model the three-dimensional motion of the limbs that would interact with the assistive device. We use a non-invasive system of calibrated cameras to capture image sequences of head motion and extract motion profiles as well as ranges of motion (Kakadiaris and Metaxas, 1996). High resolution surface geometry information about the relevant body parts is obtained by "zippering" the multiple-pass scan data acquired from a three-dimensional range measurement system (Pito and Bajcsy, 1995). Using this data products like helmets, rigid head bands, or chin cups with straps can be customized to ensure form fit to the user (Kumar et al., 1996). Other relevant information, such as the user's ability to move in different directions or constraints imposed by the environment (for example, the user's wheelchair) can also be used to further customize the virtual environment.

Virtual Prototyping

Virtual prototyping refers to the functional simulation of the user, the product, and their (physical) interaction in software for use in quantitative performance analysis of the product through the different stages of design. In the production of one-of-a-kind customized products, it is beneficial to be able to create, test and evaluate virtual prototypes and eliminate the expense of fabrication and evaluation of experimental prototypes.

To create an environment that permits the designer to integrate heterogeneous data from different sources and simulate the product along with the user, we designed a modular central user interface with bi-directional flow of parametric data among its various modules. This modular approach to software development enables us to develop stand-alone modules or add off-the-shelf packages into an integrated environment as needed. Bi-directional parametric data flow permits distributed operation of the individual modules (operating on different machines/architectures) with minimum cost overhead. Our synthetic human-user models, consisting of articulated rigid body models that reflect the geometry and the kinematics of the user, are created using Jack (Badler et al., 1993). Jack supports the simulation analysis of articulated kinematic chains like the human figures and the mechanisms of interest. Jack, augmented with a TCL/TK interface, also plays the role of the Central User Interface and facilitates the visualization via a 3D graphical interface and interaction using standard input devices. The designer can manipulate either the raw geometric and kinematic data or the derived parametric models interactively within this environment. Additionally, the designer can prescribe desired trajectories for the simulated human agent and view the execution of the motions while conforming to kinematic and physiological constraints.

The components are designed parametrically in a CAD/CAM package (Pro/Engineer, 1998) which also offers interfaces to other graphics, finite element analysis and manufacturing packages. Detailed designs of components for mechanisms are instantiated from a library of templates and exported to the central interface. Interactive modifications to the parameters of the design made in the central interface are propagated back to the original CAD model via a scripting interface. The mechanism design module, implemented in MATLAB, supports the dimensional synthesis, optimization and analysis of mechanisms and is used to create feasible design alternatives (Krovi et al., 1997; Krovi, 1998) for selection by the designer.

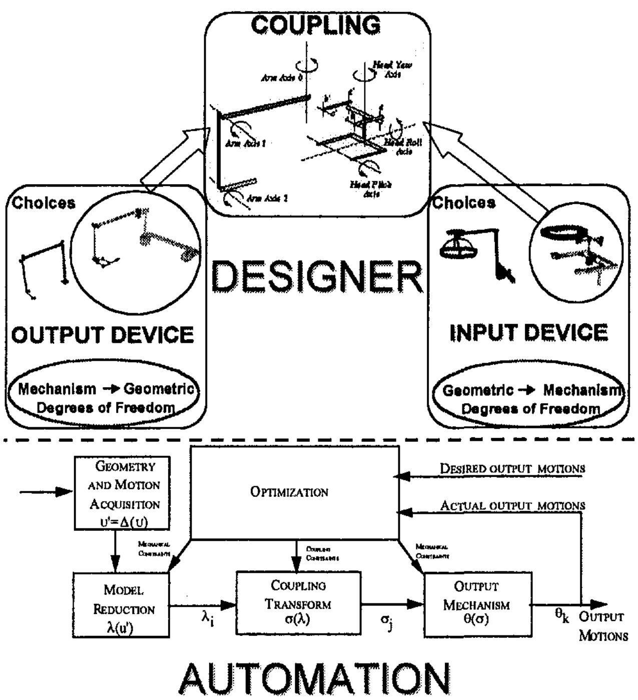

Fig. 2 Design selection and optimization

Device Design and Optimization

We have developed and automated the tools that permit a designer to take a preliminary design, convert it into a detailed design, and quickly produce prototypes for evaluation and eventually for production. The general design problem for customized teletheses is transformed into one of first selecting the types of mechanisms and transmissions and then determining the parameters that best achieve the desired output motion from the given input motion. The input subsystem captures the input motions, i.e., the three independent rotations of the head. These motions are then used to guide a three (or fewer) degree of freedom effector subsystem along a prescribed path (the spoon from the plate to the user's mouth).

The designer, aided by the unified design environment, selects a suitable configuration, the various input and effector subsystems, and the couplings between the joints of the two subsystems. The mechanism optimization then permits the parametric refinement of the design to yield an optimal mechanism to meet the design specifications. The prototype of a feeding mechanism, optimized and customized to a specific user, (Krovi et al., 1997) is shown in Fig. 3.

Concluding Remarks

Virtual prototyping enables the designer to evaluate the interactions of the personalized user model with a model of the designed product and redesign until the desired performance is achieved. Virtual prototypes additionally facilitate the involvement

Fig. 3 Photographs of the prototype manufactured at the University of Pennsylvania

of therapists, physicians and consumers in the design and evaluation of these assistive devices. This is critical since the designer may not be familiar with all the needs, constraints, and preferences of a disabled individual (Reswick, 1990). The ability to redesign of the product in response to this feedback at a very early stage can ensure the success of the product and minimize the expense of multiple intermediary physical prototypes.

In this paper, we presented a framework for the rapid individually customized design of one-of-a-kind products and outlined the issues that arise at the different phases. Although our focus in this paper was on assistive devices, the basic ideas in this paper are applicable to a variety of customized, human-worn products such as wrist braces, eyeglasses, keyboards, joysticks, sports equipment etc. Further, our virtual prototyping environment provides insight on how to design similar environments for other products.

Acknowledgments

The support of National Science Foundation, grant number MIP 94-20397, and the contributions of Dr. R. Enciso, Mr. P. Feehery, Mr. T. Heinrichs, Dr. I. Kakadiaris, Dr. R. Pito, and Mr. J. Ternus at various stages of the project are gratefully acknowledged.

References

Badler, N. I., Phillips, C. B., and Webber, B. L., 1993, *Simulating Humans: Computer Graphics, Animation, and Control,* New York, NY, Oxford University Press.

Doubler, J. A., and Childress, D. S., 1984, "An Analysis of Extended Physiological Proprioception as a Prosthesis Control Technique," *Journal of Rehabilitation Research and Development,* Vol. 21, No. 1, pp. 5–18.

Evans, M., 1991, "Magpie: Its Development and Evaluation," Technical Report, Nuffield Orthopedic Center, Oxford, England OX3 7LD.

Harwin, W. S., Rahman, T., and Foulds, R. A., 1995, "A Review of Design Issues in Rehabilitation Robotics with Reference to North American Research," *IEEE Transactions on Rehabilitation Engineering.*

Kakadiaris, I. A., and Metaxas, D., 1996, Model-Based Estimation of 3D Human Motion with Occlusion Based on Active Multi-Viewpoint Selection, *IEEE Computer Society Conference on Computer Vision and Pattern Recognition,* pp. 81–87.

Krovi, V., Feehery, P., Heinrichs, T., Ternus, J., and Kumar, V., 1997, (October 2–15), "Design and Virtual Prototyping of a Head Controlled Feeder," *Proceedings of the 5th National Applied Mechanisms and Robotics Conference.*

Krovi, V., 1998, "Design and Virtual Prototyping of User-Customized Assistive Devices," Ph.D. Thesis, Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, Philadelphia.

Kumar, V., Bajcsy, R., Harwin, W., and Harker, P., 1996, "Rapid Design and Prototyping of Customized Rehabilitation Aids," *Communications of the ACM, Special Section on Computers in Manufacturing,* Vol. 39, No. 2, pp. 55–61.

Orpwood, R. D., 1990, "Design Methodology for Aids for the Disabled," *Journal of Medical Engineering and Technology,* Vol. 14, No. 1, pp. 2–10.

Pito, R., and Bajcsy, R., 1995, "A Solution to the Next Best View Problem for Automated CAD Model Acquisition Using Range Cameras," *Modeling, Simulation, and Control Technologies for Manufacturing, SPIE Photonics East.*

Pro/Engineer, 1998, "Parametric Technologies Corporation," 128 Technology Drive, Waltham, MA 02453.

Reswick, J. B., 1990, "The Moon Over Dubrovnik—A Tale of Worldwide Impact on Persons with Disabilities," *Advances in external control of human extremities.*