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CLOSED-LOOP CONTROL IN PROSTHETIC SYSTEMS: HISTORICAL PERSPECTIVE*

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The control of artificial limbs and other restorative systems is discussed in terms of closed-loop control and sensory feedback. Feedback modalities are classified in three categories:

(1) Supplemental Sensory Feedback
(2) Artificial Reflexes
(3) Control Interface Feedback.

Historical attempts to provide sensory feedback in prostheses are discussed and put in the context of more modern efforts in this area.

INTRODUCTION

> ". . .computers may soon replace many people who work with their minds; but nothing can replace that finest tool of all, the human hand."
>
> Sidney J. Harris

Replacement of lost hand and arm function, whether by prosthetic replacement or through functional restoration of a disabled limb, is one of the most challenging problems of rehabilitation and of medical engineering. This is not surprising if one agrees the hand is "the finest tool of all" or the "instrument of instruments" as Aristotle called it. Comparisons of human limb performance with the performance of typical prosthetic replacements are discouraging enough to demoralize workers in the field. Nevertheless, the hand is so fascinating that engineers and scientists through history have gamely tried to restore the functions lost when it has been injured or amputated. That they have not been successful is probably more due to the magnitude of the problem than to lack of talent or effort on their part, although more progress could have been made had develop-

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ment work been more intense. Comparisons are not so bleak if recent results are compared with results of previous years or if current functional restoration is compared with the results of no restoration at all; but even in these comparisons there cannot be too much satisfaction.

We know when sensory feedback is absent that dexterity is degraded. Pfeiffer (25) has described the effects of anesthesia on control of the hand. A common thought therefore is that restorative systems would function better if they used closed-loop control extensively, making use of exteroceptive as well as proprioceptive qualities. Common sense, as well as preliminary studies, indicates there is truth in this. This is probably too simplistic a notion–the latest apology for lack of more success in the field–but it merits wider investigation. At the present time relatively few restoration techniques used in clinical practice have closed-loop controllers purposely designed within them. Loops are closed by the human operator through vision and incidental stimulation (audition, socket pressure, harness, etc.) but not often through design intention.

Artificial touch and primitive artificial reflex loops have been designed for prostheses and used experimentally but the clinical status of feedback of exteroceptive and proprioceptive signals is not much different today than it was sixty years ago. Herberts and Körner (12) have discussed the difficulty of trying to replace normal sensory function with artificial devices.

FEEDBACK AND MAN–MACHINE SYSTEMS

The feedback of system variables is one approach designers have for formulating new designs or for altering the performance of existing systems. Objectives of feedback may be

(a) Stability–to eliminate unwanted oscillations or to keep outputs from saturating.
(b) Performance Improvement–to optimize a performance index or to make the system "feel" better to the operator if performance indices cannot be explicity defined.
(c) Nonlinearities–to enable better performance by diminishing effects of nonlinear properties of system elements (e.g., human muscles).
(d) Parameter Change–to diminish the influence on system performance of parameter changes in open loop components resulting from aging, environmental perturbations, etc.
(e) Design–to make the system respond in some new way to satisfy a design goal.

Figure 1 is an attempt to represent the man–machine–environment interaction in a rather general way. Lambert and Hall (20) prefer to call the information input to the human operator as "feed in" and human control signals to the controller as "feedout." They reserve "feedback" for the technical portion of the system. This appears to be an unnecessary

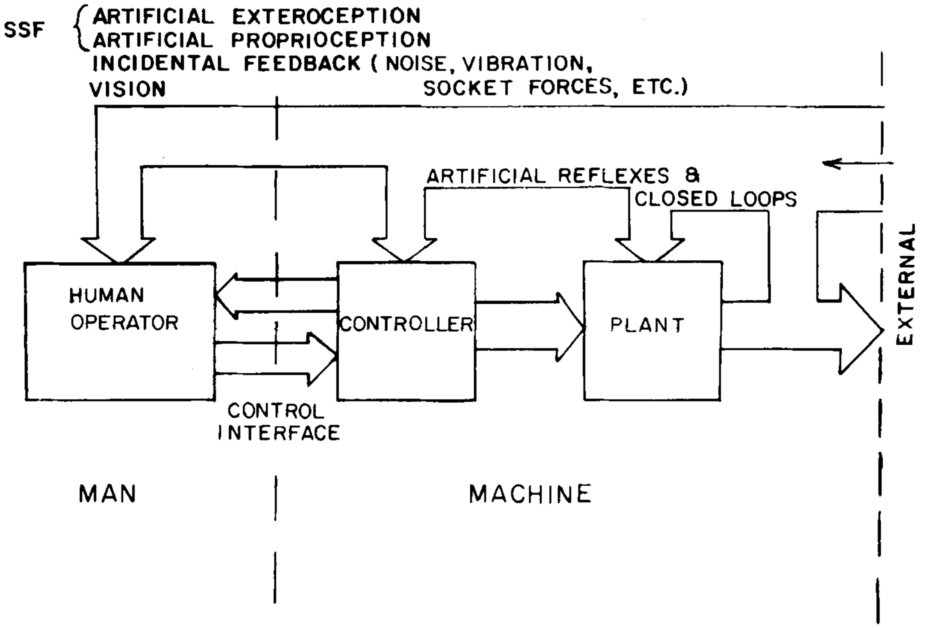

FIGURE 1. A general diagram of the man-machine system. The human operator is aware of system performance through vision, incidental feedback, supplemental sensory feedback (SSF); and through the control interface. Artificial reflexes and other closed loops may be used to improve function. If incidental feedback modalities are used intentionally they become forms of SSF.

distinction although it may be more descriptive. Even though people usually do not control restorative systems with manual inputs these systems appear to be special cases of manual control systems as defined by Sheridan and Ferrell (39), and will be so viewed in this discussion.

The human operator may derive direct information from the environment and about the machine in the environment through exteroceptors such as in vision, through artificial exteroceptors and through incidental feedback. He also may receive information through the controller by way of the control interface. Proprioceptive information may be passed over similar pathways. Artificial reflex loops that do not involve the human operator may also be present. Visual and incidental feedback is about all that is used today in the clinical application of restorative systems. The other feedback approaches have been mostly applied experimentally at research and development centers.

EARLY APPROACHES TO FEEDBACK IN LIMB PROSTHESES

Except when an amputee is blind, visual and incidental feedback are natural modes for prosthesis control and they are present with all prostheses. Visual monitoring demands attention and may create objectional mental loads on the operator of a prosthesis. Subconscious control similar to that of the normal human limbs is obviously desirable and is one reason why expanded feedback modalities have been investigated.

Simpson (41) has reviewed the remarkable properties of the human hand and arm; how they have evolved into such superb instruments. He quotes Sir Charles Bell (4) concerning the hand,

> ". . .every effort of the will is answered as instantly as if the hand itself were the seat of the will;"

Simpson convincingly brings out the importance of subconscious control of artificial limbs. How to achieve subconscious control of multiple degrees of freedom is closely tied up with the question of sensory feedback and closed-loop control.

Norbert Weiner (45) was convinced that receptors were necessary for adequate control of artificial limbs. He wrote

> "The present artificial limb removes some of the paralysis caused by amputation but leaves the ataxia. With the use of proper receptors, much of the ataxia should disappear as well, and the patient should be able to learn reflexes."

The importance of sensory feedback in prostheses was recognized long before Weiner wrote about it. Early in the century, Rosset (33) applied for a German patent concerning sensory devices for artificial limbs. The introduction to his patent application could have been written in 1980. He said

> "An artificial limb, especially a hand substitute, will always displease the user because of the missing sensation of touch, when grasping objects. Thus the amputee when using the prosthesis, depends entirely on the visual sense. . . . It is safe to assume that one of the chief reasons arm amputees prefer to do without an artificial hand is the absence of the tactile sense in the substitute. . ."

Figure 2 shows one of the mechanisms patented by Rosset. Finger pressures were transmitted directly to the residual limb by mechanical or pneumatic means so that finger pressure could be directly related to pressure on the residual limb. Conzelman *et al.* (8) filed a U.S. patent in 1948 for a similar device but using a hydraulic fluid (noncompressible) as the trans-

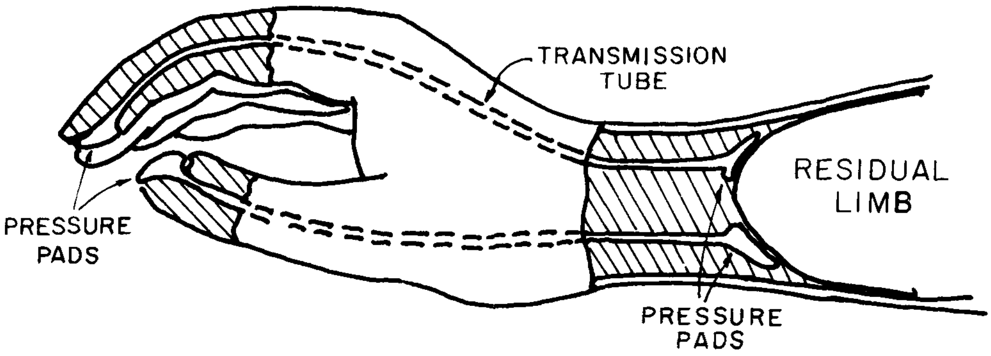

FIGURE 2. Sketch of a patent drawing (33) showing an early idea for sensory feedback in a hand prosthesis.

mission agent. This concept still seems valid today and may need to be rediscovered. It is simple in principle although it may be difficult to implement.

Martin (24) in his early book on artificial limbs mentions an approach similar to that of Rosset. He reported that an Italian manufacturer utilized the sensibility of the skin of the thorax for sensing touch by means of a "Marey's tambour" in the pulp of each finger. Marey's tambour was similar to a pneumatic version of Rosset's touch transmission device and was used as an early means for transmission of gait data (heel strike, toe-off, etc.) to a recording apparatus.

Conzelman's patent application in 1948 covered not only the hydraulic sensing device but also an electrically operated vibrator. Pressure at the fingertip closed a switch that activated a mechanical vibrator on the surface of the skin. He also suggested that vibration amplitudes could be related to pressure at the fingertip. This system is illustrated in Fig. 3.

A patent application, by Goldman (11) has described some sensory feedback ideas. He proposed to use a bundle of Bowden cables to transmit surface contour from across an artificial foot to the residual limb of a lower-limb amputee. This is similar to aspects of Rosset's patent concerning touch in fingers.

A somewhat more whimsical idea in the same patent suggested placing temperature sensors (exteroceptors) in the hand. Temperature was to be visually monitored on a dial connected to a bimetal strip. Like many ideas put forward for sensory feedback, this concept is not practical.

Bowden, founder of the Raleigh bicycle company, developed the Bowden Cable during the 1880's. Nevertheless, the Bowden Cable did not come into widespread usage in upper-limb prostheses until the 1950's when it came to be used to transmit body movement or body force to cable-driven prostheses.

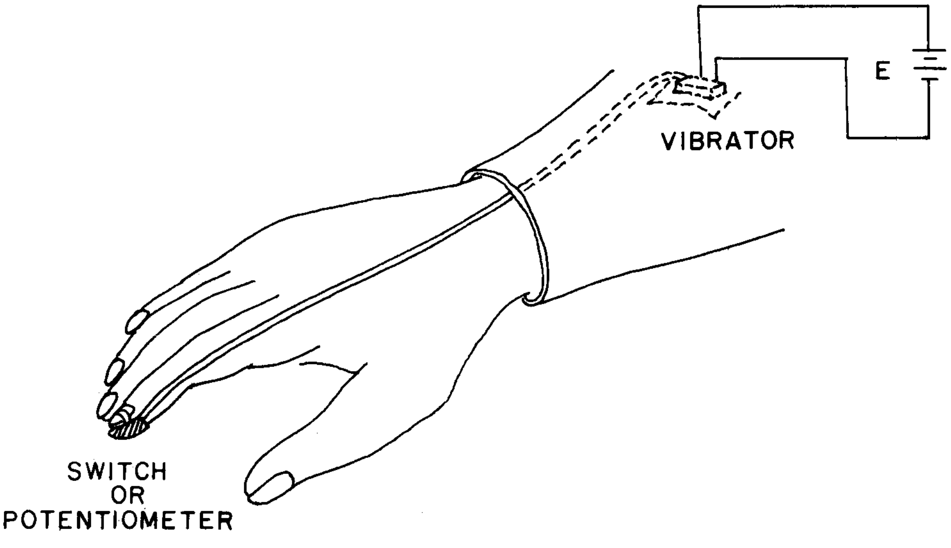

FIGURE 3. Device for sensory substitution [Conzelman *et al.* (8), sketch from patent drawing].

Interestingly, this control interface unintentionally provided a degree of proprioception and a sense of force magnitude. Because the operator is aware of the position and force in the body member that is pulling the cable he can translate this information into position or force associated with the prosthesis. Many people in the prosthetics field believe this is one reason why cable-driven prostheses can be used so effectively. This, along with simplicity and low cost, accounts for their widespread usage.

Surgical approaches to restoration have been precursors to more technical approaches. In the Krukenberg procedure the long below-elbow limb is fashioned so that the radius and ulna form two large fingers. Residual muscles are used to provide grasping force. The main advantage is the sense of touch inherent in this approach and this emphasizes the importance of tactile information.

In tunnel cineplasty (18) muscle forces can be brought outside the body by a pin inserted through a tunnel surgically fashioned in a muscle that has been released at its insertion. Natural muscle control (muscle sense), along with feedback from skin receptors help create exceptionally good man–machine interaction through this approach.

POWERED PROSTHESES

Artificial limbs powered by electricity or compressed gas have been a stimulus for the development of sensory feedback and closed-loop control because simple control methods (e.g., switches) have tended to make these devices seem like foreign appendages, not much related to the amputee's body image. The first powered components were hands developed in Germany after World War I (36). Powered limbs developed slowly until after World War II when investigations of powered components gained momentum. Of particular note in the context of this paper is the Vaduz electric hand (21). The Vaduz hand is particularly interesting because muscle bulge was used as an input to a position servomechanism on the hand to give the amputee some sense of finger position with respect to the chassis of the hand.

Reiter (29) was the first to use myoelectricity for control of powered hands. His work was followed by Battye *et al.* (2) and others. Contraction of muscles to create myoelectric signals can give the user some information about hand operation, although this was minimal in the first practical myoelectric prosthesis of Kobrinski (19) because of the on–off nature of the control. Bottomley (5) used force feedback and velocity feedback in an electric hand so the myoelectric signal had a fairly linear relationship to velocity if the hand was moving and a similar relationship to prehension force if the hand was closed. Because the myoelectric signal increases with increasing muscle force the amputee could make reasonable estimates of hand force or hand velocity with the Bottomley system. This was a good example of using feedback to diminish the influence of nonlinearities within a system. Subsequent commercial myoelectrical hand systems did not use this type of feedback; probably in a effort to simplify the systems.

The relative success of electric hand and electric elbow development and of myoelectrically controlled prostheses during the 1960's has led to many efforts during the 1970's to provide these devices with exteroceptors and proprioceptors. Also, the congenital amputees resulting because of thalidomide were a stimulus for development of methods to better control multifunctional limbs. Many of these early limbs were gas powered.

Feedback information is mostly visual and incidental in current clinical practice. Sorbye (42) has shown though that young congenital amputees who are fitted early enough develop great sensitivity to incidental stimulation. Motor vibration is apparently one of the vibrational cues they use from the prosthesis.

IDEAS IN CLOSED-LOOP CONTROL

Closed-loop techniques, other than visual and incidental feedback, can be classified (with some overlap) into three main categories. These are

1. Supplementary Sensory Feedback
2. Artificial Reflexes
3. Control Interface Feedback.

Supplementary Sensory Feedback (SSF)

Prior *et al.* (26) suggested the name "Supplementary Sensory Feedback" (SSF) to describe the artificial exteroception and artificial proprioception used to supplement visual and incidental sensory modalities (see Fig. 1). Generally SSF has taken some form of cutaneous sensation because other supplementary sensory channels are generally not practical. Von Bekesy (44) has shown that vibratory stimulation of the skin evokes sensations that in some ways parallel auditory sensations and the use of cutaneous sensation has been investigated by Geldard (10) in the broad context of its application as a communication channel. Geldard concludes that locus, intensity, frequency, and duration are parameters that can be used for vibratory communication through cutaneous inputs. These same parameters are also useful in electrocutaneous stimulation techniques.

A considerable literature has developed concerning SSF applications in limb prostheses (e.g., 3, 6, 9, 15, 16, 22, 23, 27, 30, 32, 37, 38). These studies include electrocutaneous, vibrocutaneous, and transcutaneous electrical stimulation among their techniques. Most systems give feedback information to the user concerning finger pressure, finger position, or elbow position. Results have been generally positive (i.e., the subjects like the feedback or it improved their performance on test) but not of startling impact. It appears the marginal utility may be modest with SSF.

Performance improvement may not justify the complications necessary to achieve it. Results may improve through long-term use or in congenital cases where a youngster uses the system while "growing up."

It is worth noting that a large body of knowledge related to SSF has evolved concerning the use of cutaneous communication for blind people (1, 7, 35).

Artificial Reflexes

Reflex action, the automatic response to certain conditions, is one way to assist with subsconscious control of prostheses. A synthetic reflex to control grasping force was developed early by Salisbury and Colman (34). A vibration sensor in the thumb detected the vibrations of slippage and automatically increased gripping force to stop slip. A similar idea has been proposed by Ring and Welbourn (31) in which shear is measured and used to determine an appropriate gripping force. They also suggest that it may be more appropriate to detect *incipient slip* rather than slip or no-slip conditions.

The Belgrade hand (28) used transducers in the fingers to control automatic grasping patterns. Many other ideas on automatic grasping have been developed with respect to manipulators and some of these concepts may have application in prosthetics (13).

Torque feedback in powered joints has been employed frequently in prosthetic systems (14, 23, 43). This can improve performance by making it necessary for the input signal to increase as torque due to load increases. It also can give compliance to an electric powered system, making it "feel" more natural (less rigid). Velocity feedback can also be used to improve system performance through control of damping. As already mentioned, these feedback approaches can also diminish the influence of nonlinear aspects of system components.

Feedback Through the Control Interface

The third important area of feedback has to do with provision for operator knowledge of output variables through the input mechanism (control interface). We are all familiar with this type of feedback through our experiences with power steering on automobiles and calculator keyboards where "feel" for what the fingers or hands are doing is so important in assisting with function.

The Vaduz hand system and Bowden cable controls, already mentioned, are examples of systems where knowledge of output is felt directly through the input. Other examples in the control of prostheses are the pressure demand valve (17) and the unbeatable position servomechanisms of extended physiological proprioception (epp) as described by Simpson (40). With the pressure demand valve the user of a gas activated prehension device can "feel" the output pressure through the activator valve. In this way knowledge of the gripping force is presented directly to the body part activating the input control valve. In epp the output position is tied to input position through a link (mechanical or hydraulic) so that knowledge of input position, velocity, and acceleration yields information about these quantities in the output.

Closed-loop control approaches that yield information through the control interface appear to the author to have great advantage in control of restorative systems because frequently the human operators own sensory systems are being employed and this may make control more natural in nature.

CONCLUSION

Visual and incidental feedback continue to be the major feedback modalities used in clinical practice for control of restorative systems. We still seem to be groping for better ideas and more practical implementation techniques with supplemental sensory feedback, with artificial reflexes, and with feedback through control interfaces.

An abridged history of developments in the field of sensory feedback and closed-loop control indicates we have not moved very far in the last 65 years in the clinical application of these concepts. Strides have been made in this field at research and development laboratories but much unfinished work remains if we are to bring about assistive systems that are well integrated with the persons who use them.

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