Abstract

Multi-parameter closed-loop controllers for the upper limb were operated by a C4-level SCI patient for writing. Two versions of the controller: (i) PID and (ii) adaptive, enabled writing with a pen, although neither system was easy to use. The PID preset equation constants proved fairly robust, but the adaptive equation constants enabled the system to operate under more difficult conditions.

1. INTRODUCTION

Two Beer Sheva upper limb neuroprostheses, both of them non-invasive, were developed during the 1980's in open-loop: for C4 lesion-level SCI and for C5 lesion-level, stroke, CP, MS, and TBI. The latter C5 system evolved into, and is now marketed in Europe and Asia as the Handmaster, and in North America as the NESS H200.

The C4 neuroprosthesis restored a variety of ADL. Writing was difficult however in open-loop, requiring continuous adjustment (by system-user voice command) of low-level functions required for pen manipulation: gripping and pen-paper pressure. The system was enhanced with closed-loop control capability. Two controllers were implemented and assessed: (i) fixed parameter and (ii) adaptive parameter.

Both classical control and "rule-based artificial reflexes", pioneered by Tomovic were implemented in the controller. It transpires that both the author and Brian Andrews were inspired to implement Tomovic's theories (on the upper limb and lower limb respectively) after receiving impromptu "beach" seminars at the Portoroz conference in 1983.

The controllers were designed to take responsibility for the system user and his interaction with the environment, keeping the system under control even under adverse conditions such as extension spasms of the limb; and allowing standby periods and "failsafe" response to operational breakdowns. These are requirements for unsupervised neuroprosthesis use in the home.

Since this period no further work has been carried out on the Beer Sheva C4 neuroprosthesis.

2. METHODS

2.1 System Hardware

Hand prehension/release, wrist flexion and elbow extension are generated by 12 surface electrode arrays positioned on the upper arm, forearm and hand intrinsics, each comprising 22 electrodes covering a target muscle.

Wrist joint extension is elicited by a mechanical spring. The limb is supported in an arm support attached to the wheelchair which allows a limited degree of hand movement in the horizontal plane from voluntary control of shoulder girdle muscles. Voice input commands provide a logic-based command system.

![Fig. 1: The Beer Sheva C4 Neuroprosthesis](image)

A closed-loop control capability (figure 1), was added to the system to enhance the ability to manipulate a pen and write. An instrumented pen containing 3 thin-film force sensors provides feedback of grip force, and both axial and lateral pen-paper contact forces. A potentiometer monitors elbow joint angle.

2.2 Software Controllers

2.2.1 General Control

The system user inputs high level commands such as "GRIP", "DOWN" or "UP". Implementation of the commands and control of the hand/pen/paper interaction is carried out by the controller. Several logic-based fault-sensing and correcting algorithms were added to the controller to answer specific needs and events that can occur in the home environment. For example should the pen slip out of the hand, the current intensity would rise unabated in order to attempt to increase the (non-existent) grip strength. To identify and answer this occurrence, a characteristic combination of system
conditions are sensed, the stimulation current intensity is zeroed, and the system is put on "standby" until further commands are input. Sensor input patterns detecting extension spasm result in a temporary reduction of the stimulation intensity until the spasm has passed, at which time the user can carry on writing. Algorithms were also included to account for sensor nonlinearities and drift.

Hand prehension: opening/closing motion is controlled in open loop. On command the stimulation intensity to the finger and thumb extensors is incremented to open the hand. A global stimulation intensity constant can be incremented or decremented by the system user. A further input command closes the hand by decrementing the stimulation intensity to the extensors and incrementing to the flexors with some intermediate coactivation. A command "DOWN" to lower the pen to the paper now switches to the closed loop regime.

Active control is shared between the two degrees of freedom according to their requirements. Pen/paper force is far more difficult to control, and requires a relatively high sampling rate sophisticated strategy. Gripping force is on the other hand is more tolerant and simpler to control, and a regime was developed whose aim is to keep the gripping force within reasonable limits, while responding fast to perturbations in the pen/paper force.

2.2.2 Gripping force

A "target band" is predefined within which the force is allowed to drift. If the gripping force strays outside the target band, the stimulation current intensity to the muscles involved is increased or reduced by fixed increments until the force re-enters the band.

Environmental interactions during writing cause the gripping force and the distribution of this force between the fingers and thumb to be perturbed by changes in the pen/paper force vector, particularly when the pen is lowered on to the paper, or during "vigorous" writing. These perturbations are transient and are filtered out.

2.2.3 Pen-paper force: PID Control

The primary goal of the controller is here to hold the pen to the paper continuously, with minimum contact force while the pen is moved randomly in a horizontal plane during writing. The horizontal pen movement generates a large stochastic perturbation on the monitored system force output. The force perturbation is transient in nature, but can reach amplitudes many times that of the target force. PID control of the pen-paper force by activation/deactivation of the wrist radial flexor muscle against the return spring formed the basis of the control regime. The controlling equation during pen-paper contact is of the form:

$$\Delta I = K_p \varepsilon + K_d \frac{de}{dt} + K_i \int \varepsilon \, dt$$

where $\Delta I$ is the stimulation current increment, $\varepsilon$ is the error between the measured and the target pen/paper force, and $K_p$, $K_d$, and $K_i$ are constants. Iterative hand-tuning of the equation constants was carried out experimentally.

2.2.4 Pen-paper force: Adaptive Control

The PID equation constants are adapted as a function of the variance of the disturbance in the pen/paper force, thus assessing the mood of the person and to a lesser extent the operating characteristics of the system plant. The pen/paper force trace during continuous writing at typical speed generally takes the form shown in figure 2.

![Figure 2: The pen/paper force characteristics during writing.](image)

### TABLE 1

<table>
<thead>
<tr>
<th>Adaptive Controller PID Parameter Adjustment Protocol</th>
<th>Control Parameter</th>
<th>Average amplitude of positive phase of force wave</th>
<th>Average duration of positive phase of force wave</th>
<th>Parameter Increment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_p$, $k_i$</td>
<td>small and short</td>
<td>large and long</td>
<td>$\rightarrow$</td>
<td>large and positive</td>
</tr>
<tr>
<td>$k_p$, $k_i$</td>
<td>large and short</td>
<td>long</td>
<td>$\rightarrow$</td>
<td>large and negative</td>
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<tr>
<td>$k_p$, $k_i$</td>
<td>large and long</td>
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</table>

The pen/paper force feedback is contaminated by high amplitude stochastic disturbances as the pen is moved horizontally in different directions and speeds during writing. It is difficult to feedback on-line information on the success or failure of the control system, as this imposed stochastic force drowns reliable information on the response characteristics of the system. Rather the pen/paper force feedback primarily indicates the characteristics of the volitional writing motion, and to a lesser extent, the ability of the controller to cope with it.

The character of the pen/paper force is assessed periodically at approximately 10 second intervals by the average of the wave amplitude and of its duration. Adaptations are carried out on the...
equation parameters according the conditions listed in table 1. Limits were placed on the range of values of the PID equation parameters. These limits covered realistic range of values for each parameter. While the pen is raised between strokes, the assessment and adaptation procedure is frozen.

The controller effectively adapts to the mood of the system user, the type of writing, the type of pen and paper, and to its own performance.

3. RESULTS

3.1 PID Controller: Figure 3 shows the gripping force and pen-paper force and also the stimulation current intensities as the pen is lowered to the paper and writing commences.

![Fig 3: PID Controller Performance during Writing](image)

Poor controller performance manifests itself in several possible ways: as a sluggishness of response, resulting in slow correction of pen/paper contact forces, "digging in" of the pen into the paper or wedging of the pen into the paper during the forward stroke, and the tendency of the pen to "hover" slightly above the paper for short periods, particularly on the return stroke. This behavior characterizes the system where the gain is set too low. An over responsive performance where the system gain is set too high can induce instability or resonance where the pen appears to "bounce" on the paper at the natural frequency of the system (1 Hz approx.). This is detrimental to writing, but useful for drawing dotted lines.

These phenomena can be eliminated by tuning the control equation constants KP, KD, and KI to suit the prevailing system conditions.

3.2 Adaptive Controller: Figure 4 shows an example of writing with the adaptive controller.

![Fig. 4: Writing with the Adaptive Controller](image)

The letters are on average 1.5 cm in height, and the note took about 10 minutes to write. The writing itself is difficult as no direct (or proprioceptive) connection exists between the movement of the shoulder girdle and the resulting end point motion of the hand. The wobbly lines are a result both of this and of variations in the pen-paper contact force as the pen stroke direction changes. This is particularly evident in circular pen strokes.

The conditions for adaptation of the controller parameters in effect caused an increase in the "springiness" (increased gain with reduced damping) of the control where the system user writes slowly and carefully, while "deadening" (reduced gain with increased damping) the control where the system user writes fast and jerkily. These adaptations tend to shift the system poles away from the prevailing wave frequency of the writing to avoid system resonance, correcting the pen/paper force during slow careful writing and drawing, but effectively filtering out the force waves during fast writing and scribbling.

4. DISCUSSION AND CONCLUSIONS

The PID controller was found to behave fairly robustly, but to occasionally experience an "off day" where the preset constants controlled the system unsatisfactorily.

Assessment of the adaptive controller on one patient shows the controller to respond as intended, "deadening" the system in response to a lively operator, and "spicing it up" where the operator writes lethargically.

References