A Novel Single Digit Manipulator for Prosthetic Hand Applications

Jeffrey E. Erickson, *Graduate Student Member, IEEE*, Kathryn J. DeLaurentis, PhD, *Member, IEEE*
and Mourad Bouzit, PhD, *Member, IEEE*

Abstract— **Herein, we report a lightweight manipulator with potential application as a prosthetic finger. Our design features lightweight construction using low cost actuators. To reduce power consumption, force and motion actuation are separated. Low cost miniature DC motors provide motion for the digit, while a magnetorheological fluid piston acts as a force brake. This combination of actuators improves efficiency and reduces weight. Control is provided by networked low cost microcontrollers, and is separated into high level coordination and low level position control. The end device will be low cost, efficient, and lightweight with low failure cost and easy substitution of parts for customization.**

I. INTRODUCTION

Those of us who have full use of our hands may take for granted the value of our dexterity. We don't think twice about how to open a door, open a bottle, shake a hand, or pick up a cup of coffee. For those who have lost a hand, these can be very frustrating tasks, especially for those who lost the hand suddenly and traumatically.

Technology has progressed to the point where devices that have the dexterity of the hand, measured in degrees of freedom (DOF), can be artificially produced. Also, electronics have progressed to the point where major processing power can be packed into increasingly smaller spaces. These combine to provide the platform for the development of an artificial prosthesis capable of mimicking the natural human hand [1-2].

Several of these devices have garnered attention in recent years. Among these are devices by a group at the University of Southampton, England, and the Shadow Robot Company, also in England.

The Southampton device uses capstans and linkages to control the curling of each digit [3]. Using this method restricts the digits motion to a single trajectory. While there may be three joints in each finger, since a single actuator is used, the path the finger follows does not and cannot change from one actuation to the next. This limits the ability of the device to conform to objects of irregular shape. Further, it prohibits some orientations of the hand found in nature.

The Shadow hand employs pneumatic actuators. In fact, this hand reproduces all the motion of the natural human hand [4]. However, due to the weight of the pneumatic compressor, and the bulk of the actuators, this device is far too heavy and large to be used as a prosthesis. Also, the actuators are located almost entirely in what would be the forearm. This requires wires and linkages to transmit the mechanical motion to the fingers of the hand.

II. APPROACH

Taking previous devices into account, and analyzing the desired characteristics of prostheses, we came to the following conclusions regarding hand prostheses.

First, the device needs to be lightweight. Not necessarily the weight of a hand in vivo, but at least light enough for a person to use daily for several hours without fatigue.

Second, the device must be dexterous. Each digit in the hand has three degrees of freedom (four if the abduction-adduction at the palm in included). Therefore, we want our digit to have at least three degrees of freedom

Third, the device must generate force similar to that of the in vivo counterparts. This means that a single digit should generate 8-10N at peak.

Given these design goals, we began to develop our general approach to this novel single digit manipulator; combining actuation and smart material braking in a dexterous model.

A. Novel Actuation Method

Many, if not all, of the existing devices use single actuators to generate both motion and force at the same time. However, there are times when the system is generating a lot of force when only motion is required, such as closing against air. Conversely, there are times when force is needed with little motion, for grasping heavier objects. The result is two disadvantages: energy loss and increased bulk. Therefore, we have decided to separate force and motion actuation in this new device.

This approach has two principal advantages. These arise from two different, but not exclusive, modes of operation.

When closing against air, as mentioned above, the small DC motors need to generate little torque while moving the joints of the digit. Thus, they draw little current. However, if these same motors were used to maintain a grip, the power dissipation would be very high, as the motors would essentially be stalled, turning the motor into a low impedance

Manuscript received April 9, 2007.

J. E. Erickson is a Graduate Student in the Graduate Program in Biomedical Engineering, Rutgers, the State University of New Jersey and the University of Medicine and Dentistry of New Jersey, Piscataway, NJ 08854 USA. (e-mail: jee7s@eden.rutgers.edu)

K. J. De Laurentis is an independent researcher with a Doctor of Philosophy in Mechanical Engineering from Rutgers, the State University of New Jersey.

M. Bouzit was with the Department of Electrical and Computer Engineering and the Department of Biomedical Engineering, Rutgers, the State University of New Jersey, Piscataway, NJ 08854 USA. Currently, he is a research associate at ISTIA at the University of Angers, France.

resistor. This presents both an electrical inefficiency and a hazard, as the motors could overheat and damage the motor itself or other components in the device.

On the other hand, force brakes cannot move the joints of a manipulator. However, they are very effective at maintaining the position of the joints against outside forces. When maintaining a grip, the force brake would be able to maintain high force output with less current and less heat dissipation than an electric motor.

Therefore, by using these two actuators and controlling them to utilize each in their best mode we gain three advantages over single actuator design. First, power consumption is reduced because the force brake generates more force per watt than an electric motor. Second, weight is conserved since the mass of the small electric motors and force brakes combined is less than larger electric motors necessary to generate an equivalent force. Third, being able to use smaller motors allows us to design the structure of the device to minimize mechanical transmission lengths.

B. *Structure*

The design of an actuator to mimic the human finger would seem a straightforward task, and grossly speaking it is. However, the alignment of actuators, transmission systems, wiring, and control hardware leads to many possible configurations.

Since the intention in this project is to maximize the degrees of freedom (DOF) of the device, a minimum of three actuators is needed to create the three independent DOF of the finger. Previous designs have employed wire transmissions or pneumatic actuators. These both require the actuators to be located in what would be the palm of the hand. This requires long mechanical transmissions, typically by wires. Wires stretch and fatigue, varying the performance of the device over time.

Rather than centrally locate the actuators in the palm, we chose to locate each DC motor in our design near the joint it actuates. This allows for a more mimetic weight distribution, and reduces the transmission length to near zero. This is possible through the use of the small DC motors, which can be mounted inside the medial and proximal links of the artificial finger, and the palm. Each of these motors drives the joint distal to it. The force brake is located in the palm, and brakes the digit with a steel wire tendon (see Fig. 1).

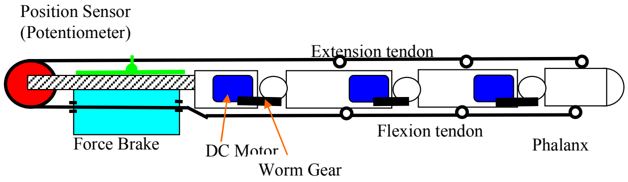

Fig. 1. Overview of the mechanical configuration of the device. This is a first approximation. The worm gear indicated has been replaced with a newly developed transmission.

C. *Sensing and Control*

Each of the joints is feedback controlled. Position is sensed using Hall effect sensors mounted in the structure at each joint. This information is acquired via analog to digital conversion and fed into a microcontroller.

Also, force sensors will be mounted on the palmar surface of the digit for force feedback control. The palmar surface designed is flat, providing a mount for a variety of sensors.

This input data is integrated and processed in the microcontroller. The controller then generates motor drive signals to control the position of the joints, and a drive signal for the force brake to control its behavior. Applying software control makes changes in the control algorithm easy via reprogramming, rather than having to reconstruct hardware components. This approach also allows for a variety of control, ranging from PID to state space to adaptive and intelligent algorithms.

D. *Software Architecture*

The software on the microcontroller is separated into three principle components: communication, control, and maintenance.

Maintenance routines are used to catch interrupts and errors generated by the software and hardware of the microprocessor. This is largely a background operation, similar to an operating system.

The control portion is the low level feedback control mentioned above. This provides for the accurate positioning of each joint, and control of the force brake.

Communication routines are implemented for using both universal serial bus (USB) and inter-integrated circuit bus (I^2C). These are provided for future expansion of the device. The I^2C bus is for networking of several control processors. USB is used for high level preprogrammed control inputs and task level control.

E. *Task Level Control*

Herein, we refer to high level pre-planned action by the system as “Task Level Control.” We add this aspect of our design in anticipation of further development and linking of several digits in coordination.

The final application of this work would conceivably be in a prosthetic hand. As such, we have prepared for the networking and coordination of several control processors. This will be a decentralized system with one powerful processor conducing high level calculation, communication, and control. This processor would coordinate several slightly less powerful low level feedback controllers. While this has not been implemented as such yet, the current design is adaptable to such a networking coordination control scheme.

III. MECHANICAL DESIGN, FABRICATION, AND ACTUATORS

A. Design

The artificial digit was designed using AutoCAD Mechanical Desktop solid modeling environment.

Each segment of the digit has a void at the distal end for mounting of the motor, along with the female end of a hinge mechanism used to attach the segments. The proximal end of the link has the male end of the hinge mechanism. The axis of rotation of this hinge is not on the centerline, as in the natural hand, but rather located on the palmar face of the digit. This was necessary to provide sufficient clearance for the motor and transmission system. The female end of the hinge also includes a small cylindrical void for mounting the hall effect sensor. Both ends of the hinge have concentric 2.1mm axle holes, which provide 0.05mm radial clearance for a 2.0mm steel dowel pin. The male end of the hinge is sized for a 0.1mm clearance with the female end.

Each segment has the same cross-section, which is 23.5mm wide and 15mm high. The shape is oblong and symmetrical about the axis of the digit. The palmar and dorsal surfaces of the digit are flat. The palmar flat is 20mm wide, and the dorsal flat is 13mm wide. Also, at each end of the segments, there are small triangular brace processes to support this hinge structures. This has the added benefit of providing a more conformational shape.

The center of the cross section is hollow, to accommodate a small DC motor. The motor has a rectangular gear box 12mm wide and 10mm high. Behind the gear box, the motor housing is oblong with 12mm diameter arcs on each side and a 10 mm height. The center void of the digits is sized to the dimensions of the motor provided by the manufacturer for a tight fit. The proximal end of this void is continued through the length of the digit. This void both reduces weight and provides a path for control and motor wiring.

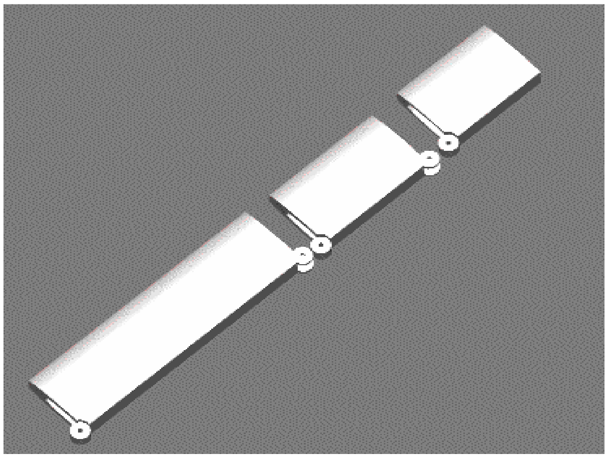

Fig. 2. Expanded view of the AutoCad model of the digit. Note the axis of rotation of each digit located at the palmar surface. Also note the voids for the motor cavities, visible on the left end of each segment.

The distal segment, which does not have a motor mounted in it, is 23mm from proximal hinge axle center to tip. The medial segment is 30mm from distal hinge axle center to proximal hinge axle center. The proximal segment is 45mm from hinge axle center to hinge axle center. (See Fig. 2 for additional detail from this section.)

B. Fabrication

The solid models were fabricated using fused deposition modeling (FDM) on a Stratsys 3000 Fused Deposition Modeler. The medium was ABS plastic, drawn to 0.4mm diameter.

This produced a good set of parts, but post fabrication modification and assembly was necessary to meet the tolerances and clearances of the design.

After soldering motor supply wires to the motor terminals, the motors were press fit by hand into the motor void in each segment. The axle holes in the hinge were aligned, and secured with a 2.0mm diameter stainless steel dowel pin 18mm in length. The metal axles were sealed using Loctite 480 adhesive to prevent movement during use.

This method was repeated for all three joints.

Fig. 3. The first fabricated device. Note some design changes noted in the text from Fig. 2 are visible here. The dark circle on the distal-medial hinge axis is the hall effect sensor magnet. The black rods are attached to motor shafts for clarity.

C. Actuators

The aforementioned DC motors are one of several Sanyo 5VDC miniature geared motors available from Solarbotics. There are three such motors available, all with identical dimensions. The torque outputs are available from 78mNm to 217mNm. Since each of the motors are identically dimensioned, swapping of one motor for another of a different torque is done with minimal effort. In this first evolution of the design, we chose Sanyo GM11 gear motors, which have 78mNm of torque.

For a force brake, based on previous designs and experience by colleagues [5], we have chosen to use magnetorheological fluid (MRF) pistons. MRF is a smart material that is essentially micrometer sized ferrous particles suspended in a suitable non-corrosive liquid. Application of a magnetic field by wire coils causes these ferrous particles to respond, having the effect of increasing the viscosity of the fluid by orders of magnitude. The fluid becomes so viscous that its behavior leaves the linear Newtonian range and the piston seizes. When the magnetic field is not present, the piston acts like a fluid damper. This allows for switching of the brake on and off, without mechanical components like a clutch. Also, since the brake is electrically switched, the response time is on the order of milliseconds.

IV. CONTROL DESIGN

In order to have consistent software from one processor to another, and to have similar supporting hardware, we decided to use a single series of processor. Microchip's PIC18 series has several options that have both USB and I^2C modules, as well as firmware for each.

An x86 PC with custom control software is used to communicate with a Microchip development board. This board has a PIC18F4550 processor mounted with supporting hardware, external oscillator, and indicator LEDs. This processor also has an I^2C master module, though the associated pullup resistors are not provided on board. However, expansion headers and solder pads allow this board to be interfaced with additional electronic components. Currently, this processor simply repackages the USB information into an I^2C bitstream.

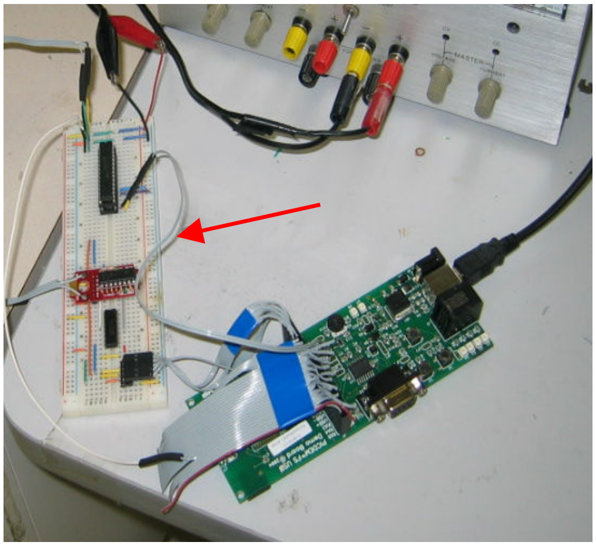

Fig. 4. Layout of electronic hardware. The green board to lower right is the Microchip development board with PIC18F4550 processor. USB cable to PC runs from the development board to the right. On the white breadboard to the left is the PIC18F2431 (near the top) and the L293 PWM motor driver (red board toward the bottom). The gray ribbon cable with blue tape is a parallel interface for position recording. The thin gray wire pair indicated by the arrow is the I^2C bus.

As previously mentioned, we use the I^2C link as a bridge from the controlling x86 computer to the low level controller.

The low level controller is a Microchip PIC18F2431. This processor has an I^2C slave module, to receive the bitstream from the PIC18F4550. Motor drive is provided via on-chip pulse width modulation (PWM) peripherals. Also, it has A/D inputs for the hall effect position sensors.

Sensor inputs are buffered using 741-type operational amplifiers. The PWM motor drive signal coming out of the processor is amplified with a type L293 PWM motor driver.

Currently, the controller is a PI control system. However, this can easily be expanded to state space or adaptive control in software.

V. TESTING

Testing began using just the USB enabled processor. This allowed for implementation of single joint control using a kinetic model, while the final version of the digit was being developed in the virtual environment.

Next, we proceeded to test in I^2C bus and the USB processor conversion routines. These functions parse the USB packet for transmission via the I^2C bus.

Finally, as the last functional test, we transferred the control software from the USB processor to the low level processor.

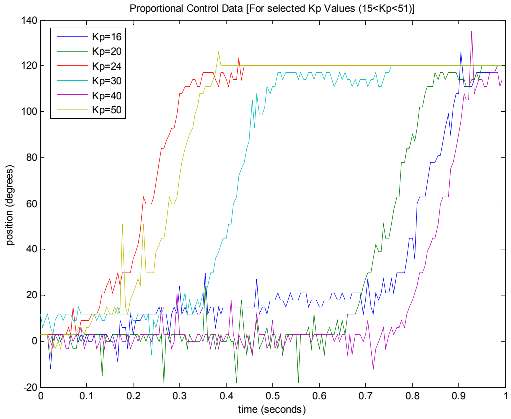

Fig. 5. Example of data collected under proportional feedback control. Several gains are shown here, with increasing proportional gains to the left.

Following this validation, single joint testing using the two processor architecture was conducted (see Fig. 5). Control of the single joint was attained, but some mechanical interference and friction was encountered, yielding a less than optimal result.

We are currently completing implementation and testing of a novel compliant transmission system. Following validation of this new mechanism, we hope to integrate it into the control scheme for the digit.

Unfortunately, due to time constraints and availability of fabrication facilities, the force brake we intend to use has yet to be fabricated. However, previous testing by our laboratory on similar devices has shown their ability to accomplish the tasks we see the brake performing.

VI. DISCUSSION

The nature of this device, the degrees of freedom it exhibits, the lightweight design, and the separation of force and motion actuation are in accordance with our design goals. Beyond that, however, the device is exceptionally low cost. Each of the three motors costs less than US $20. Also, the small parts required to assemble the device total no more than a few dollars. Even with FDM costs included, we estimate this device costs the producer less than US $300 to produce.

In addition, the failure cost is minimal. Since the transmission method is compliant, it is less likely to fail. Even if such a failure occurs, the cost to repair the transmission is a matter of cents of materials, not dollars. Even if a motor or structural part were to fail, due to the modular nature of the design and the ability to swap the motors, even such a catastrophic failure would cause the producer less than US $100 to repair.

These two features, combined with the abilities of this artificial digit manipulator, offer a low cost, dexterous, durable alternative to more expensive existing models. This will hopefully reduce costs in future prosthetic hands, making more advanced actuators available to a wider audience of users.

VII. FUTURE PLANS

In the coming months, we hope to finalize this design and test a fully viable single digit manipulator. Also, we hope to construct the planned force brakes and test their performance in the planned configuration.

Plans also include the continued development of the control systems, networking of several single digit manipulators, and coordination through the aforementioned task level control.

ACKNOWLEDGMENT

J.E. Erickson would like to thank, in addition to his co-authors: Mr. John Petrowski for his assistance with FDM and post fabrication modification; and Dr. Evangelia (Litsa) Micheli-Tzanakou, for her support and guidance.

REFERENCES

[1] Pons, J.L. et al. (1999) Multifingered dextrous robotics hand design and control: a review. *Robotica* 17:661-674.

[2] Craelius, W (2002) The Bionic Man: Restoring Mobility. *Science* 295:1018-1021.

[3] Kyberd, P.J., Light, C.M., Chappell, P.H., Nightingale, J.M., Whatley, D., & Evans, M. (2001) The design of anthropomorphic prosthetic hands: a study of the Southampton Hand. *Robotica* 19:593-600

[4] Shadow Robot Company. (2003) Design of a Dexterous Hand for Advanced CLAWAR Applications. *Proceedings of the 6th Int'l Conf on Climbing and Walking Robots (CLAWAR):* Catania, Italy; September 17-19, 2003. (Provided by Shadow Robot Company, December 2005)

[5] Winter, Scott (2006) "A Haptic Force Feedback Glove Using Magnetorheological Fluid." Master's Thesis. Rutgers, The State University of New Jersey, May 2006.