THE INTRINSIC HAND – A 22 DEGREE-OF-FREEDOM
ARTIFICIAL HAND-WRIST REPLACEMENT

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1.0 INTRODUCTION

Now is an exciting time to be in the field of Upper-Limb Prosthetics. Due to the limited function of current commercially available upper-limb prosthetics and the increased incidence of amputation injuries being seen in Operation Enduring Freedom (OEF - Afghanistan) and Operation Iraqi Freedom (OIF) a number of new initiatives have been put into place to develop replacement arm/hand systems capable of replicating the function of the human arm and hand. In particular, the Defense Advanced Research Projects Agency (DARPA) has a four year initiative, “Revolutionizing prosthetics 2009”. The goal of this program is to develop a replacement arm/hand system capable of enabling soldiers with limb loss from OEF/OIF the capability of returning to service similar to the way those with lower ankle-foot disarticulation have been able to do for years. Led by the Johns Hopkins University Applied Physics Laboratory, the goal of this project is to design a fully functional biomechatronic analog to the human hand and arm. The device must be capable of duplicating the function of the original limb and withstand the rigors of daily living. Our involvement on this team is to develop robust and anthropomorphic hand-wrist prostheses capable of dexterous manipulation suitable for use by persons with all levels of trans-radial limb loss. Where as to date most anthropomorphic high degree of freedom hand manipulators place their actuators in the forearm [8, 9], this paper details the results of placing the actuators intrinsic to the hand.

2.0 DESIGN PARAMETERS

The design of a twenty two degree of freedom hand-wrist prosthesis is a multifaceted problem involving a large number of disciplines and different areas of expertise. Specific considerations were made towards mass, speed, volume, and power [1, 16]. Although the weight of a single adult hand accounts for about 0.75% of their total body weight [17, 18] hand prostheses must be significantly lighter if it is expected to be worn [13]. With respect to the hand, it’s hardware must be able to fit in a 50th percentile female’s hand volume but produce torques of that of a 50th percentile male, generate more than 89.0 N of pinch force, generate 311.0 N of cylindrical grasp force, generate 4.6 Nm of torque for lateral prehension and actuate at least 270 degrees/sec. Whereas for the wrist, the specifications were to generate 13.5 Nm for flexion/extension, generate 6.0 Nm for Radial/Ulnar deviation & wrist rotation and actuate at 120 degrees/sec under no load conditions.

3.0 DESIGN

In accordance with the program’s design specification, the completed design is able to fit into the hand volume of a 50th percentile female. For fabrication however, the program specified that a 50th percentile male’s volume be used. The number of degrees of freedom that were able to be actuated is dependent on the number of drives that could be fit into the allotted
space. To get the necessary function, custom Maxon EC 13x13 brushless DC motors with integrated gearing were developed specifically for this project. With a mass of 13g, given a 12V supply voltage, each motor can produce a no-load speed of 30,000 rpm with a stall torque of 12 mNm. A motor was placed in each finger, eight in the palm, and three in the thumb for a total of fifteen EC 13 motors in the hand and four underactuated joints at each of the distal fingers. Actuation of the three degree of freedom wrist was produced with three modified Axi motors.

3.1 MCP

The prosthetic hand device has independently-driven flexion and extension at each of the four Meta Carpal Phalangial (MCP) joints. The actuator for each of these joints consists of a brushless DC electric motor with a wolfrom planetary-gear transmission. See Figure 1. To get the planned 4.5 Nm of torque at each MCP joint, the design used an integrated a 510:1 wolfrom-belt drive transmission. The range of motion of the drive is 90° flexion and 45° hyperextension. Room for hall-effect sensors integrated into the design for absolute position sensing. Each MCP motor has its own controller mounted at close proximity in the palm. The controllers utilize flex circuits to allow for complex packaging arrangements.

3.2 Abductors

The prosthetic hand device has independently actuated Abduction and Adduction for the Index, Ring and Little Finger. The actuators for this function consist of the same motor, controller and transmission used at the MCP joints. See Figure 1. The output of the Ab-Adduction actuator is coupled to each corresponding finger MCP housing via a spur gear train. The range of motion for the Index and Ring Finger in the Abduction direction is 20 degrees from the neutral position. The range of motion for the Little Finger in the Abduction direction is 40 degrees from the neutral position.

3.3 Fingers

The design of the finger drive was based on housing the finger’s motor in the proximal phalange and coupling the distal and medial phalanges through a ball screw linkage system. Maintaining the anthropomorphic functionality, the range of motion of the proximal intermediate phalange (PIP) joint is 88° flexion while the distal intermediate phalange (DIP) is capable of 89° flexion. The design is able to fit within the volume of a 50th percentile female (17.5mm width). Experimental tests have shown that while anchored at the proximal phalange, the finger is capable of lifting a 1Kg mass at the distal phalange. The PIP joint is capable of generating over 4.7Nm of torque at 360 °/sec at 15V while the DIP is capable of generating over 2Nm of torque with a speed of 270 °/sec at 12V. In addition to the motor and drive system, room for the electronics was integrated into the design.

3.4 Thumb

In addition to the fingers, dexterous manipulation also necessitates a multi-degree of freedom thumb. Instead of introducing a third drive system to the hand; the design philosophy of the thumb is centered on the finger’s MCP belt-wolfrom. The prototype design yielded a functional four degree of freedom thumb with a mass of 250g which was planned to generate 4.7 Nm of torque at each joint with a speed of 270 °/sec at 12V. The thumb’s joint range of motion are 105° at the IP, 65° at the MCP, 48° Radial Abduction and 90° Palmar Abduction.
3.5 Palm

The palm is the chassis of the hand system by housing the motor drives and controller boards of each MCP, the Ab-Aductors and the thumb’s palmar abduction drive. The palm consists of a clam shell design with two halves that fasten along the coronal plane. See Figure 3. The thumb, fingers, and wrist are a modular subsystem of the hand and are independently mounted to the palm using mounting posts.

![Figure 1](image1.png)

Figure 1 – Finger Module with Distal Finger (1), MCP Joint (2) and Abductor Joint (3)

3.6 Wrist

The first anthropomorphic intrinsic three degree of freedom wrist is capable of ±60° flexion/extension, -45° ulnar deviation, 15° radial deviation and 360° rotation. Similar to the hand, the wrist assembly was anthropomorphically designed to fit into the volume of a 50th percentile female but has a planned torque output of a 50th percentile male. The wrist uses three modified Axi 2204/54 brushless DC motors housed in each joint. See Figure 2. Torque generation at the flexor and deviator units primarily originates from a wolfrom drive while the rotator uses a cycluidic drive. In addition to the drive units, each joint housing also included a motor controller board and slip rings were planned for a CANBUS communication architecture to provide power and communication to the hand via the wrist.

![Figure 2](image2.png)

Figure 2 – Intrinsic Wrist with Flexor Unit (1), Deviation Unit (2) and Rotator Unit (3).
4.0 ELECTRONICS

Two levels of control were developed for this project; housed in a vest (Figure 3), the higher level provided the control algorithm for each of the lower level controllers and monitored power usage, while the lower level controllers, connected to the higher level controller via breakout board, provided local control to its associated motor and sensor suite. Two classes of motor controller boards were created for each type of motor, small motor controllers (SMC) for each of the fifteen DC motors, and large motor controllers (LMC) for each of the wrist’s Axi motors. All control boards were custom designed and developed for this project at the Applied Physics Laboratory at Johns Hopkins University. Absolute position sensing at each joint was intended using Hall-effect sensors. Finger tip sensing was planned for using custom commercially produced strain gauge array with a thermistor at the Index, Middle and Thumb [13] and force sensing resistors at the Ring and the Little fingers. All sensors connected to an SMC or LMC but were ultimately not implemented due to lack of time.

5.0 CONCLUSION

A multi-degree of freedom hand prosthesis capable of dexterous manipulation has been presented. Our novel motor drive approach enabled us to integrate virtually every biological hand-wrist degree of freedom into the design within a 50th percentile female’s volume. In its first conception, the intrinsic hand nearly pushed existing DC motor and gear technology to its limits but due to lack of resources, the wolfrom drive efficiency was found to be 10%. Moreover, significant reliability issues originated from running the wires over axes of rotation to the unavoidable tight electronics packaging inside the palm cavity. The fully mechanically functional Intrinsc Hand was unveiled to the public on July 18th, 2007 during DARPA Tech in California. Future work includes improving the mechanical efficiency of the drives, improving electrical robustness and increasing joint compliance. Although not all of the design goals were met, the time between design concept to functional prototype donned by a test subject was less than one year.
6.0 REFERENCES


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