

SANDIA REPORT

SAND2011-0438

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Printed January 2011

Advanced Dexterous Manipulation

for IED Defeat:

Report On the Feasibility of Using the ShadowHand for Remote Operations

Robert J Anderson

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Advanced Dexterous Manipulation for IED Defeat: Report On the Feasibility of Using the ShadowHand for Remote Operations

Robert J. Anderson
Robotic & Security Systems
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-MS1125

Abstract

Improvised Explosive Device (IED) defeat (IEDD) operations can involve intricate operations that exceed the current capabilities of the grippers on board current bombsquad robots. The Shadow Dexterous Hand from the Shadow Robot Company or “ShadowHand” for short (www.shadowrobot.com) is the first commercially available robot hand that realistically replicates the motion, degrees-of-freedom and dimensions of a human hand (Figure 1). In this study we evaluate the potential for the ShadowHand to perform potential IED defeat tasks on a mobile platform.

ACKNOWLEDGMENTS

This report and work described within was sponsored by TSWG and DSTL under WFO Proposal 064090730. Points of view or opinions contained within this document are those of the author and do not necessarily represent of official position of TSWG, DSTL or of the Dept. of Energy.

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NOMENCLATURE

CAN	Communication Bus for embedded systems
DARPA	Defense Advanced Research Projects Agency
DOE	Department of Energy
DOF	Degrees-of-Freedom
DSTL	Defense Science Technology Laboratory
IED	Improvised Explosive Device
IEDD	Improvised Explosive Device Defeat
PID	Proportional-Integral-Differential
SNL	Sandia National Laboratories
ShadowHand	Shadow Dexterous Hand from Shadow Robot Company.

1.0 INTRODUCTION

Anthropologists have argued that it is not the brain that makes humans unique, but the human hand. They conjecture that the advanced hand operations required to hunt have forced the evolution of the brain. Whether this is true or not, there is not doubt that the human hand is an amazing mechanism.

For IEDD operations, hands are needed to perform many tasks. First there is simple grasping of common items: ranging from briefcases, trash-can lids, bricks, aerosol cans, plastic bags, car mats, to batteries and wires. Objects may weigh a fraction of a kilogram, or tens of kilograms. They may be rigid or flexible, rough or smooth. Hands are also needed for manipulation. This can included opening office doors, opening car doors, unzipping carry-all bags, turning keys, pulling levers, or deploying sensors. Finally hands are needed for deploying tools. This may include insertion of fiber optic probes, removing screws with a screw driver, taking samples with a spoon, or opening packages with a knife. Because all of these actions can be performed by human hands it is natural to consider duplicating a hand with a mechanical replica when operating a remote mobile manipulator.



Figure 1: The Shadowhand

1.1 Robot Hand Development History

Replicating human hands in robotic form has long been a passion of robotics researchers. Dr. Ken Salisbury developed his robot hand during graduate work at MIT, and continues to explore innovative new hand designs at Stanford. The Salisbury hand has been used by many research labs throughout the 80's and 90's including Sandia National Labs. The UTAH/MIT hand was developed as collaboration between SARCOS research, the Center of Engineering Design at the University of Utah, and the Artificial Intelligent Laboratory at MIT. A full-force feedback exoskeleton system was developed to for the hand to allow direct telemanipulation for this design. Not surprisingly, both hands utilized a tendon based approach that is highly similar to the Shadowhand robot. Tendons allow the actuators to be located far away from the fingertips, keeping the fingers light and the hand workspace uncluttered. What is not shown in the pictures below (Figure 2.) is the large motor system and tendon support structure required to move these two mechanisms.

Historical Hand Designs



Stanford/JPL Hand (1983)
(Salisbury Hand)



UTAH/MIT Hand (1984)

Figure 2: Historical Hand Designs

From our personal experience in operating the Salisbury hand and from correspondence with Utah/MIT hand researchers the verdict is the same: maintaining these complex tendon based systems can be a nightmare. Tendons stretch and fray, and the sheer number of cables, motors, and control surfaces that need to be maintained is daunting. These early designs provided fodder for numerous research papers, but lacked the robustness and reliability for practical operations such as IEDD tasks.

The last two decades have seen continuous improvements in core technologies that impact robot hand design. Enhanced rare-earth motors, improved sensing, compact electronics, improved cable materials, and better fabrication methods have led to the advanced robot hand designs shown below in Figure 3.

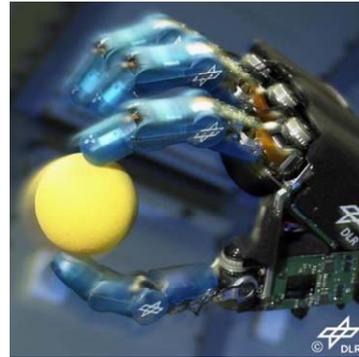
Both NASA and the German Space Agency (DLR) have taken a “cost is not an issue” approach to building custom robot hands to enable telerobotic servicing for space operations. The Robonaut system (http://www.nasa.gov/mission_pages/station/main/robonaut.html), can lift an

impressive 20Kg, and is tightly coupled with a telerobotic master controller system. After years of research and millions of dollars the first Robonaut system is scheduled for its first space mission this December 2010 – but not to perform any mission tasks. It will be flown to continue research objectives and to provide some positive public relations for the program.

Modern Hand Designs



Robonaut 2 Hand



The DLR Hand II



The BarrettHand



University of Tokyo High-Speed hand

Figure 3: Modern Hand Designs

The DLR hand (http://www.dlr.de/rm/en/desktopdefault.aspx/tabid-3802/6102_read-8923/) embeds the motors and controls inside the hand itself. The result is a much-larger hand, but with a much tighter integration of sensing and controls and less impact on the forearm. It has morphed from its space teleoperation focus into a testbed for advanced impedance control concepts and autonomous control, and is currently being deployed on mobile manipulator platforms such as “Justin”. (<http://www.youtube.com/watch?v=ZPwpGpMoAxs>).

The Tokyo robot hand (<http://www.k2.t.u-tokyo.ac.jp/fusion/index-e.html>) pushes the limits in speed, bandwidth and tactile sensing. Although not attempting to match a human hand in kinematics, nor matching the payload capacity of the KLR and Robonaut hands, it far exceeds all in response. It has demonstrated advanced dexterous tasks such as straw-twirling, ball dribbling,

and cell-phone juggling. The entire finger tip surface is covered with a sensor mesh that can detect exact points of contact.

The Barrett Hand (www.barrett.com) represents the only commercially available system in the group, and has proven itself in the market as a successful hand design over the last decade. It includes integrated motors, finger clutches that allows fingers to wrap and lock around an object, and an innovative rotating finger design that can cause fingers to work in conjunction or in opposition. The entire system is powered using only four motors.

1.2 The DARPA Dexterity Initiative

In 2009 the Defense Advanced Research Projects Agency (DARPA) put out a Broad Area Announcement for Autonomous Robotic Manipulation the focuses on improving dexterity of robot systems. (<http://spectrum.ieee.org/automaton/robotics/robotics-software/darpa-arm-program>) The high level sample task was to develop and demonstrate a robot system that could reach blindly into a duffle bag and pull out a hidden semi-automatic pistol. The proposal was designed as a competition in which six software teams would initially compete and get downselected as the process continued. Each software team would receive identical hardware: initially a whole arm 7-DOF manipulator from Battett technologies, a Barrett hand, a stereo vision system and a 3-D ranger. In addition, three hardware teams would focus on providing a rugged, low-cost design for a robot hand.

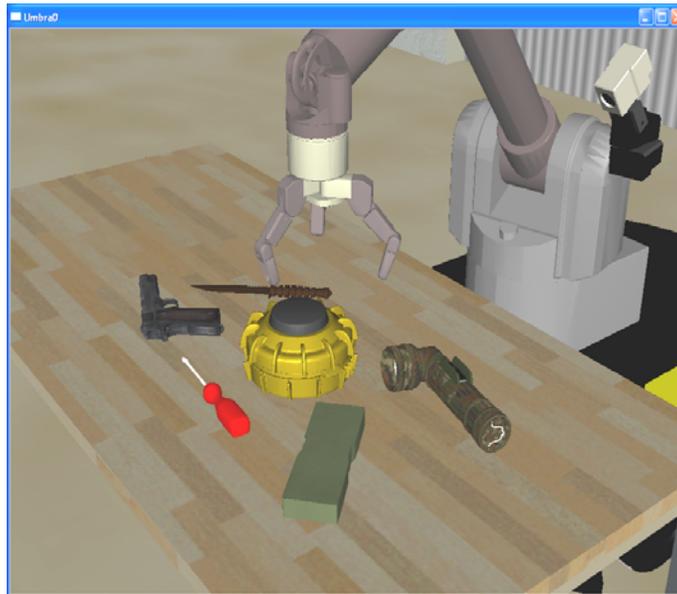


Figure 4: Phase 1 Grasping Tasks for DARPA.

By 2014 the winning teams will be focusing on manipulation using an integrated pair of Barrett arms on a mobile platform and using a newly designed robot hand. The target tasks are similar to those required for IEDD operations, but rather than having a person in the loop, DARPA wants these systems to perform the tasks autonomously.

As part of the hardware portion of this task, Sandia is teaming with Stanford University to develop a new hardware hand that is less costly and more effective than the current BarrettHand

option. It is too early to tell whether the DARPA initiative will result in substantial gains in dexterity – but the choice of hardware and the competitive nature of the program make this an exciting program to watch.

2.0 GRASPING REQUIREMENTS

The IEDD operator doesn't need an anthropomorphic hand out in the field. All they need is capability – with the human hand being a good representative of the capability they desire. But what constitutes a good grasping device?

Cornell and Uof Chicago researchers are able to obtain good grasps of various oddly shaped objects using nothing more than coffee grounds, a rubber balloon, and a pneumatic pump. (<http://www.sciencedaily.com/releases/2010/10/101025161140.htm>). For their device, good grasps are obtained due to substantial contact area with the grasped object, and a high friction rubber surface.

Grasping researchers considers a grasp to be good if the grasped object won't move under small force arbitrary torque and force perturbations – the higher the tolerable perturbations, the better the grasp. Mathematically this can be derived by looking at the of friction cones at the point of contact. A grasp is a “force closure grasp” if the motion of the grasped object is completely constrained by these cones.

If the contact is “frictionless” than it takes a minimum number of four contact points to constrain a rigid body. With friction, a body can be constrained with just two contact points – but they have to be the right locations on the right type of body.

The tool “GraspIt” (<http://www.cs.columbia.edu/~cmatei/graspit/>) from Columbia University has been developed to analyze grasp quality and provide visualization and planning tools for grasping. In the image below (Fig. 5) we see the effective grasp cones at each point of contact a DLR robot hand grasping a flask.

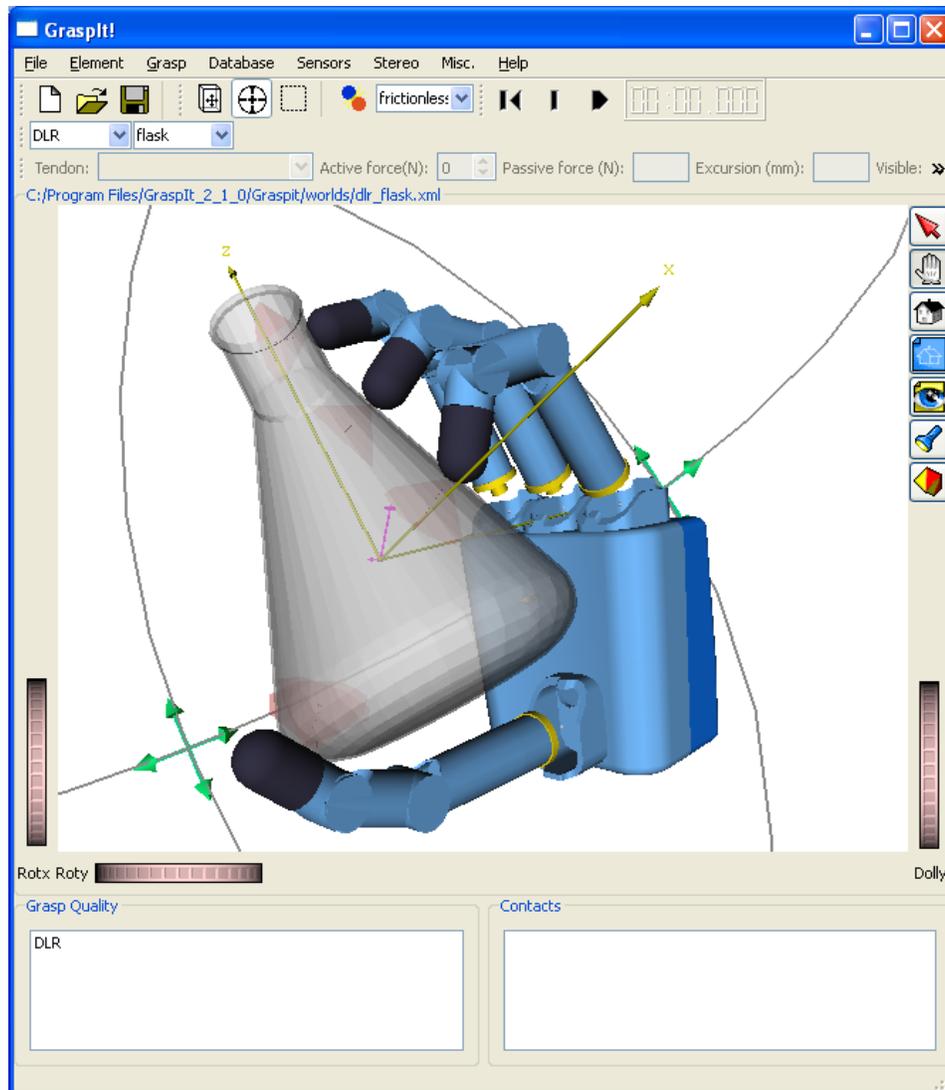


Figure 5: DLR Hand grasping a Flask in Graspl

The grasp above is considered stable but is still quite precarious. Finger based grappers like those of the DLR hand typically have a single point of contact per finger due to the local convexity of the finger tips. Even four points of contact provides little grasping surety.

In the image below, the Barrett Hand has grasped a wine glass. Its finger surfaces are nearly flat, but more importantly it uses its inner finger surfaces to make a grab. In this image eight different points of contact are made with the wine glass to ensure a solid grab. Maintaining contact at multiple points and from all sides of an object is the key to a good grasp.

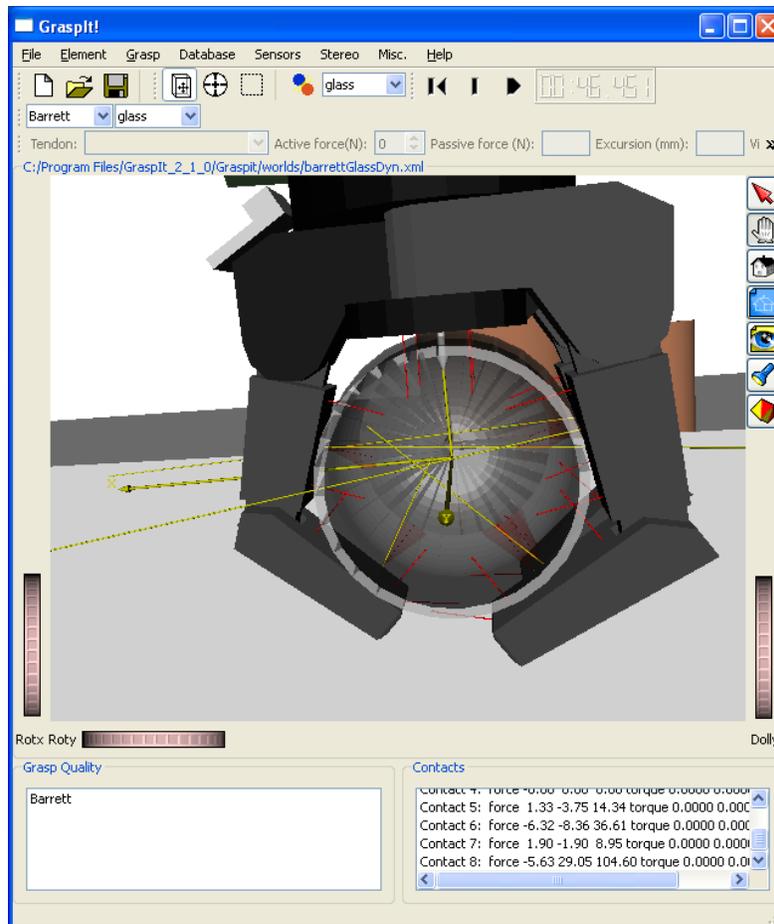


Figure 6: Barrett Hand in Graspl!

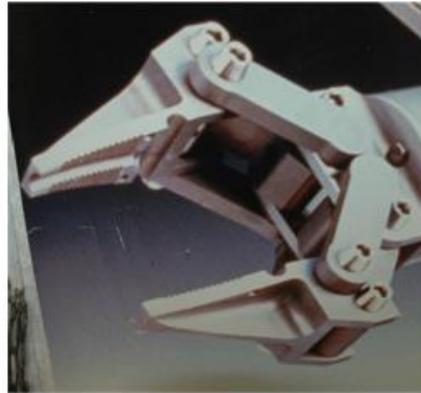
2.1 Existing Grasping Capabilities

Most existing mobile manipulators use a simple parallel jaw gripper actuated by a single motor. Some examples of these grippers are shown in Figure 7. None of these use convex finger tips like the DLR, Salisbury and Shadowhands, but instead use mostly flat surfaces with concave features. Flat surfaces provide multiple points of contact when grasping box-like shapes and additional V-grooves provide multiple points of contact when grabbing cylindrical objects. The Remotec F6A gripper can easily grab boxes that are 25 cm in width with surety, while its V-groove features is used to grab cylindrical objects such as pipes. The Titan gripper has fine serrated teeth and a T-bar in-lay on a set of wide parallel surfaces. The T-bar allows it to deploy standard tools such as pipe-cutters that can exert extreme forces and moments. The Warrior gripper from I-robot was designed with multiple teeth in rows. It can create multiple high-contact points of contact using its powerful gripping force. The Remotec/Sandia “M2” robot uses a pyramid gripper with crossing V-grooves. This allows it to pick up standard tools having a pyramid attachment, grab cylinders along axis or off-axis, and fully contain any spherical object.

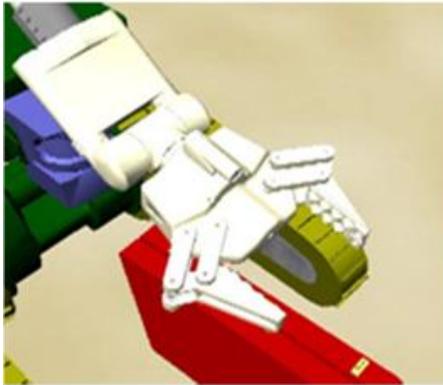
Parallel Jaw Gripper Designs



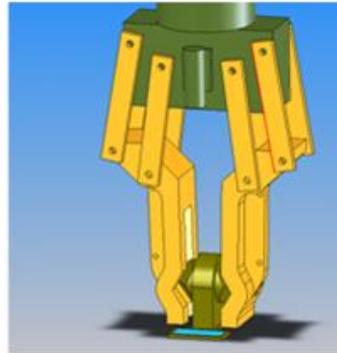
Remotec F6A
Gripper
(V-Groove)



Schilling Titan
Gripper
(T-Bar Pickup)



I-Robot Warrior
Gripper
(Multiple Teeth)



Remotec/Sandia
"M2" design:
"Pyramid Grip"

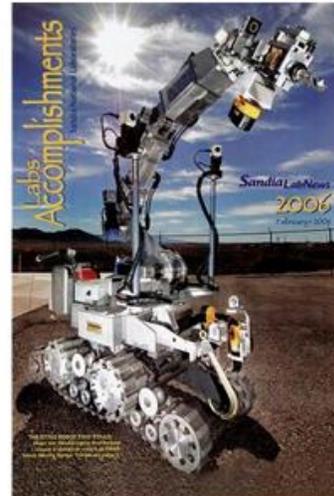


Figure 7: Parallel Jaw Gripper Designs

For a robot hand design to compete with these existing telerobotic graspers it will need to be able to provide equivalent points of contact to surround and restrain an object.

3.0 THE SHADOWHAND

The Shadow Robot Company (<http://www.shadowrobot.com>) is a small London based robotics company that evolved from the passion of a small number of robotics hobbyists over a decade ago. These developers decided to pursue a robotic hand design as an engineering study in complexity. If they could demonstrate prowess in recreating the most complex and sophisticated tool nature ever evolved – the human hand – then they had proof they could handle much simpler design tasks as well.



Figure 8: Shadowhand

3.1 System Description

The Shadow Dexterous Hand (ShadowHand) is a gorgeous piece of engineering. It contains twenty-four moving joints, twenty actuators, twenty one embedded micro-controllers, and both position and force feedback sensors for every joint. All of these are packaged in a format that matches the size and length of a human hand. Finger tip surfaces have a soft rubber surface for better friction contact, and even details such as fingernails have been included.

ShadowRobot has been evolving hand designs for most of the last decade. Over this period they have iterated and refined many of the core technologies needed for a hand. This include embedded finger magnets for hall-effect based position sensing, hand kinematics, cable drive routing and handling, internal micro-controller fabrication and layout, and spring-loaded finger tips.

All of their prior designs however, were based on pneumatic air muscles (<http://www.shadowrobot.com/airmuscles/overview.shtml>) typically called McKibbens muscles. The air muscles provide substantial strength, closely mimic the human muscle tendons, and provide natural compliance. Unfortunately, controlling twenty active joints with pairs of antagonistic muscles requires forty of these mechanisms, which cannot be reasonably packaged for deployment on the end of a robot arm¹. For this reason, ShadowRobot was tasked to develop their first all-electric robot hand to meet potential mobile robot deployment requirements. We received the company's first all-electric hand design for evaluation as part of this activity.

3.1.1 Overall Layout

The Shadowhand has twenty actuated motors summarized in the table below. The index, middle, ring and pinky fingers have identical lengths and parts, but are staggered at different positions off of the palm. The pinky finger is attached to an additional palm fold joint.

Table 1: DOFs and Kinematic Range for Shadowhand

DOF	Name	Motion Range (degrees)
1	Wrist Pitch	-40 to 20
2	Wrist Yaw	-30 to 10
3	Thumb Roll	-60 to 60
4	Thumb Curl	0 to 75
5	Thumb medial pitch	-15 to 15
6	Thumb medial yaw	-30 to 30
7	Thumb distal pitch	-10 to 90
8	Index Yaw	-25 to 25
9	Index proximal pitch	-10 to 90
10	Index medial/distal pitch	0 to 90 (+0 to 90 on distal)
11	Middle Yaw	-25 to 25
12	Middle proximal pitch	-10 to 90
13	Middle medial/distal pitch	0 to 90 (+0 to 90 on distal)
14	Ring Yaw	-25 to 25
15	Ring proximal pitch	-10 to 90
16	Ring medial/distal pitch	0 to 90 (+0 to 90 on distal)

¹ The air muscle version of the Shadow Dexterous Hand is actually narrower than the electrical version, but is far longer and requires eighty pneumatic valves and a source of compressed air.

17	Pinky palm fold	0 to 40
18	Pinky Yaw	-25 to 25
19	Pinky proximal pitch	-10 to 90
20	Pinky medial/distal pitch	0 to 90

Each motor is connected to a pair of cables via an integrated tensioning device that drive the muscles in agonistic and antagonistic directions (Figure 9).

The backbone of the hand’s internal communication is Controller Area-Network (CAN)-bus. This is the highly successful serial protocol developed for the auto industry that allows a system of intelligent control units to communicate to each other. CAN-bus is used to talk to a host computer, and for the palm processor to relay position information to each of the motor control units.

3.1.2 Electrical Design Layout

The ShadowHand uses custom motor controller board based on PIC microcontrollers. The palm unit is larger and more sophisticated than the remaining units. It uses a high-speed serial communication to each of the hall-effect sensors that are located on each moving joint. It processes this data and then transmits the position information to the joint controllers across the CAN bus. The individual motor controllers drive the motor units, read strain gauge data, and close the local torque feedback loop. These motor control units also receive joint position data from the hand control unit to close an outer position feedback loop.

3.1.3 Sensor Layout

Shadowrobot has developed and fabricated miniature magnets that embed in the finger tips, and via hall-effect sensors can provide position feedback in an extremely compact package. We analyzed the data coming of these sensors and obtained smooth noise-free joint resolution of a fraction of a degree – which appears to be far more rugged and robust than a potentiometer solution might provide. The only potential issue is for the magnetic fields generated by one finger to impact the fields of an adjacent finger and cause false readings to occur. Shadowhand engineers assured us that this can exist, but the impact is considered minimal. We did not further analyze this effect.

3.2 System Limitations

3.2.1 Mechanical Issues

The hand uses a series of shrouded cables to transfer motion and power from the motors to the finger tips. The four fingers each incorporate a spring loaded distal finger tip to allow the medial and distal joints to be controlled with a single motor. If the medial joint is constrained upon grasping closure, the combined joint motor will then drive the distal joint to full closure. This realistically recreates the substantial coupling that exists between distal and medial joints in a human hand, but makes precise closure control more difficult since it depends on the behavior of a passive joint. This problem is minor, however compared to the problems with variable friction.

The cable tendons controlling finger motion are routed through the hand and wrist and into the motor base. As the fingers bend, the torque required to overcome cable friction can be quite large and depends on the position of other joints. Servo gains that work well for one pose results in sluggish or unstable behavior when in a different pose.

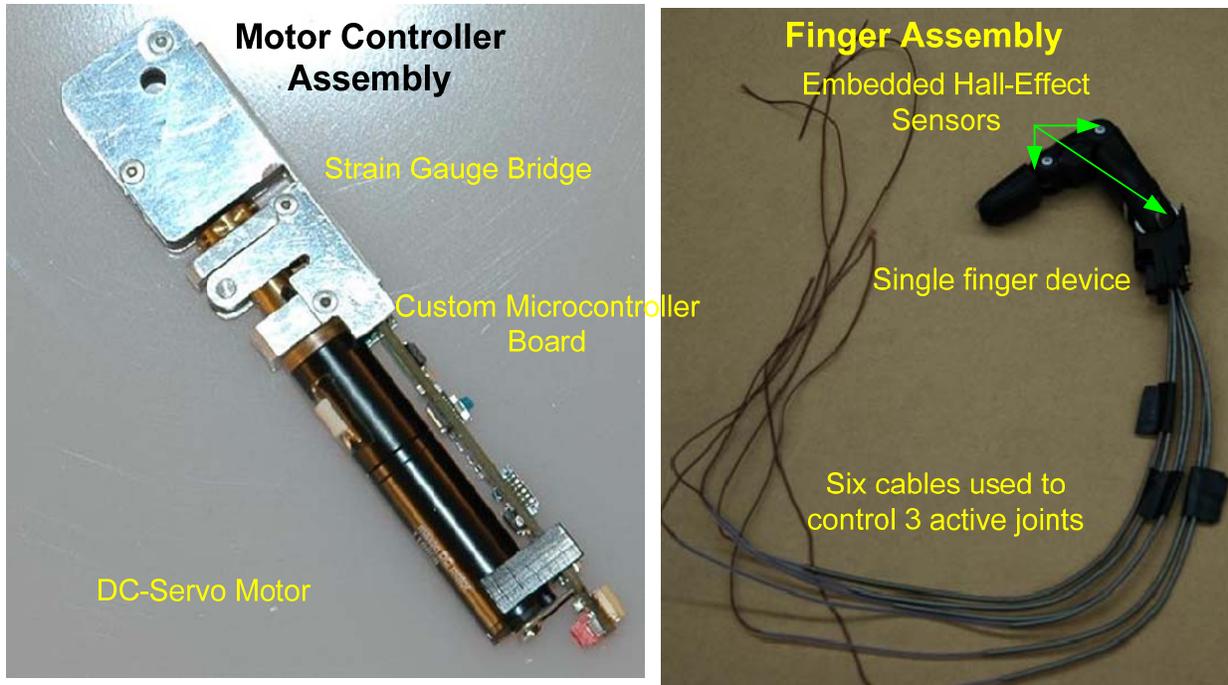


Figure 9: Finger Assemblies

During the course of this evaluation period we received an upgrade to help address this problem. Shadowrobot’s immediate solution was to implement a simple gain-scheduling approach that they called a “U-Map”, which regulates the total gain based on the position of a single joint.

Unfortunately there were issues in performing the upgrade, and we never had the time or resources to complete the U-Map tables for the joints. From a control perspective, however, this approach did not seem ideal, since friction effects are a function of the entire hand pose. A more effective approach might be an adaptive friction estimation system that could provide feedforward compensation for expected friction effects based on finger pose. Rather than just throttling a single gain, the system should provide a look-up table for position and velocity gains to apply as a function of position and provide a feedforward term.

3.2.2 Communication & Control Limitations

As with any serial communication system, there are bandwidth limitations to CAN, and this effects system performance. For the Shadowhand the communication rates for transferring position information from the hall-effectors sensors was limited to 90Hz.

The 90Hz base communication rate is substantially lower than position feedback for most robotic feedback devices. Conventional robot motor servos operate at well above 1 KHz. High feedback rates are important since position feedback is differentiated in software to provide an effective velocity feedback term to stabilize the motor response. If this sample rate is too low noise and vibration creeps into the system and performance is limited.

The ShadowHand system that we received uses a two-layer Proportional-Integral-Differential (PID) control loop. The inner PID torque loop sought to control forces by measuring the torque from the strain gauge bridge and feeding back any error between desired and expected results. This control loop should help minimize the impact of friction in the motor gear box, and provide a closer measurement of actual joint torque. An outer position control loop was then used to regulate position error response. The servo gains could be configured by the developer, but in its default configuration many of the gains were set to zero. In addition to the standard linear gains, the controller had settings for a force limit threshold, an integral wind-up limit and deadband controls.

3.2.3 Experimental Tracking Performance

We evaluated the ShadowHand system first at the DSTL facility with the Shadowrobot folks providing the demonstration, and secondly at Sandia labs after being refurbished by Shadowrobot. During this interim it was also evaluated by the University of Birmingham based on the experiences of student volunteers.

Our experience was consistent across the board. It is difficult to command precise motion grabs with the glove. The task of achieving finger/thumb opposition required watching the hand closely and attempting to reverse engineer its motions. The hand could make “power grabs” consistently with the glove, but these require little precision. The thumb was particularly hard to control and often required awkward ministrations by the operator to get the thumb to respond. The claim from Shadowrobot was that this was a calibration issue, but their engineers did little better during the preliminary demonstration.

We knew that no hand exactly matches any standard glove nor matches the kinematics of the Shadowhand, but the glove/hand combination seemed to have more severe tracking issues than could be explained by bad calibration. Figure 10 below shows a series of commanded hand gesture and the corresponding had response. From these pictures it is easy to see the wide range of motion of the thumb device and the variation in tracked positions.



Figure 10: Glove Tracking Performance

4.0 SHADOWHAND INTERFACE DEVELOPMENT

The out-of-the box solution provided by Shadowhand and the sponsors consisted of the cyberglove the hand and the controller PCs. There was poor correspondance between hand positions, and no hope of controlling forces. There was no graphical representation of the hand commands in virtual space, and no means to send grasp pose commands from our robot consoles. With this interface it would not be possible to isolate problems, nor to evaluate which system components were working well, and which needed to be reengineered. Clearly, we would need to write software to provide the interfaces we required to evaluate the hand. Luckily, the engineers at Shadow Robot Company have an open source mindset and were fully willing to help.

4.1 Graphical interfacing

As delivered, the Shadowhand system had no graphical representation capability. From initial testing it was obvious that there was a large disparity between the motion being commanded from the Cyberglove and the motion being executed with the Shadowhand. To better understand the reasons for this disparity we needed to visually represent the commanded position of the Shadowhand.

Using engineering models of finger geometry obtained from ShadowRobot, we built a kinematic replica of the robot within Sandia's Umbra framework. Polygon reduction was performed on the initial model to create the model shown below (Figure 11).



Figure 11: Umbra based graphical model of the ShadowHand.

We wrote a software driver that connects to the hand's CAN-bus and interprets the low-level communication packets being generated by the palm microcontroller. This microcontroller is the receiving house for all of the hall-effect measurements for joint position. It receives the raw data, processes it, and then sends it on to the motor control units. A passive CAN-packet sniffer can reside on the bus, decipher the communication packets and monitor the position without interfering with hand operations. In our installation we used a commercial CAN-bus interface module (PCAN-USB from Peak www.peak-system.com) attached via USB to a laptop computer

Once connected and with driver software written we were able to monitor the CAN bus and process the data packets. It was then possible to drive the hand with the cyber glove and monitor the tracking performance using the virtual avatar representation. It was clear that the correspondance between hand commanded position and actual hand location was quite good – our poor tracking performance was a problem inherent in the glove system, and not in the hand itself.

4.2 Configuration Tool Development

We knew that the hand could accurately track positions, but what about force response? A hand grasping tool needs to do both well. The ShadowHand was designed with integrated torque loops at the motor servo level, but how effective was it? Understanding low-level torque control performance requires a deep understanding of the internals of Shadowhand controller. Using the PCAN-USB device and packet definitions from ShadowRobot we were able to sniff control packets and come to a better understanding on how they implemented their control algorithms.

To aid this inquiry, we developed a Python based configuration tool that allowed us to fully setup the gains on each motor controller (Figure 12). Each individual motor channel can be selected, exposed and configured using this interface. Servo gains for the sensor (strain gauge) and motor (position) loops can be fully setup, downloaded to the microcontroller and saved to disk.

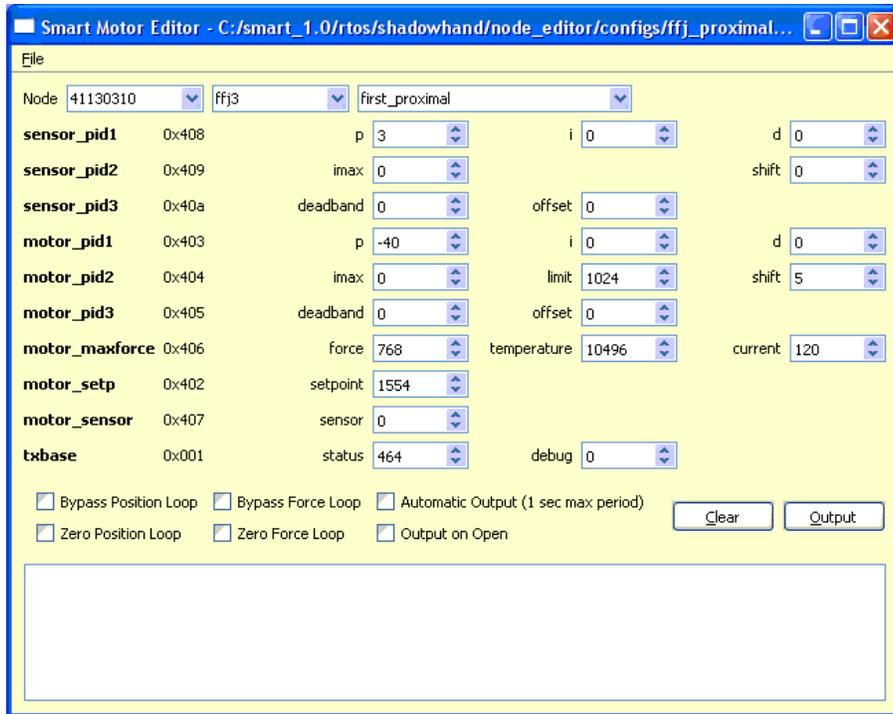


Figure 12: Sandia Developed Configuration Editor for ShadowHand...

By tweaking gains on each channel it was indeed possible to obtain a smoother response to applied forces and to even command forces. For every setting that was explored, however, there were trade-offs. A finger may have performed well in its mid-range, and then go unstable when fully extended. Or it may have robust position control and have poor response to force disturbances.

4.2.1 Motion/Force Plots

Using the factory gain settings established by ShadowRobot we recorded the output position as a function of input commanded position for a number of the joints. These plots are shown in the figures below (Figure 13-15). In these plots some of the performance problems in the ShadowHand are illustrated. The robot can overshoot in reaching targets, it tends to jump in 3 to 10 degree hops, and the tracking performance is highly dependent on the position of the finger joints. In each of these plots the blue line represents the set-point command, the cyan line represents the retransmit, and the red and green lines represent the medial and distal joint responses. These joints work in conjunction to track the set-point, and thus our focus is on the smoothness of the response, and not on the absolute tracking behavior.

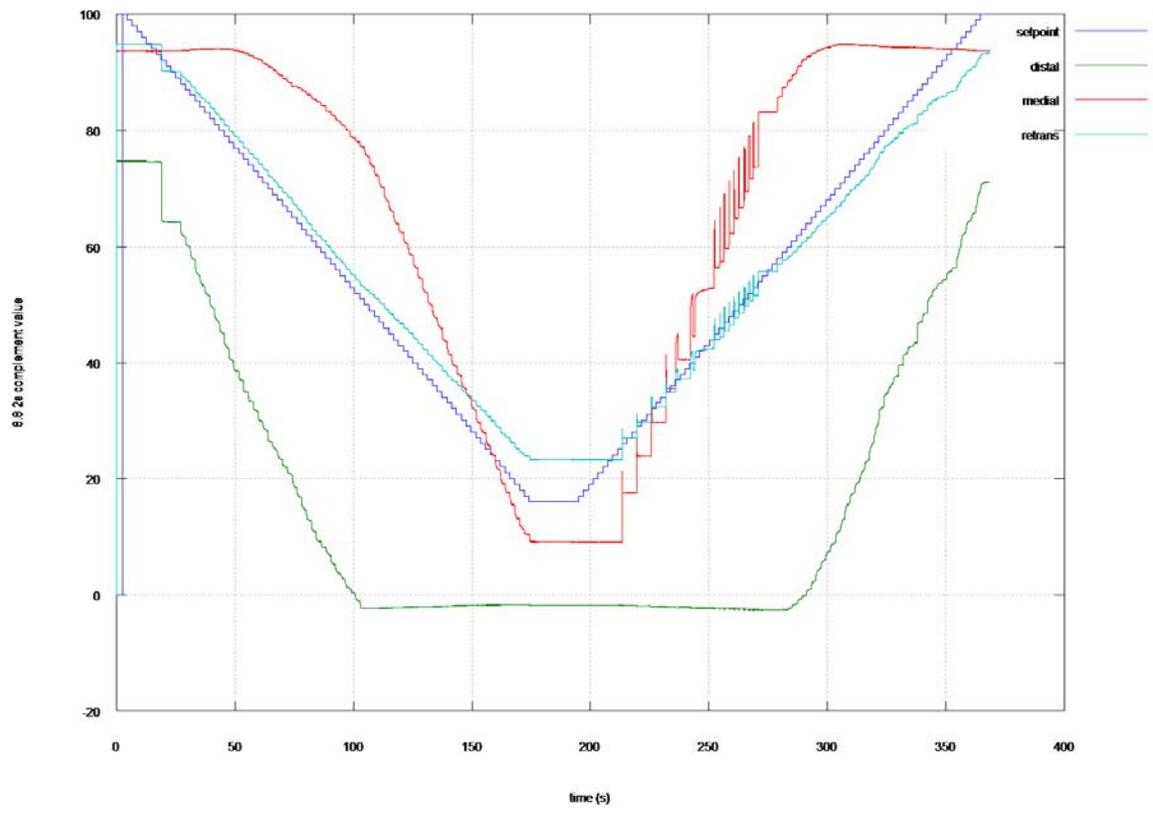


Figure 13: Index Finger Response.

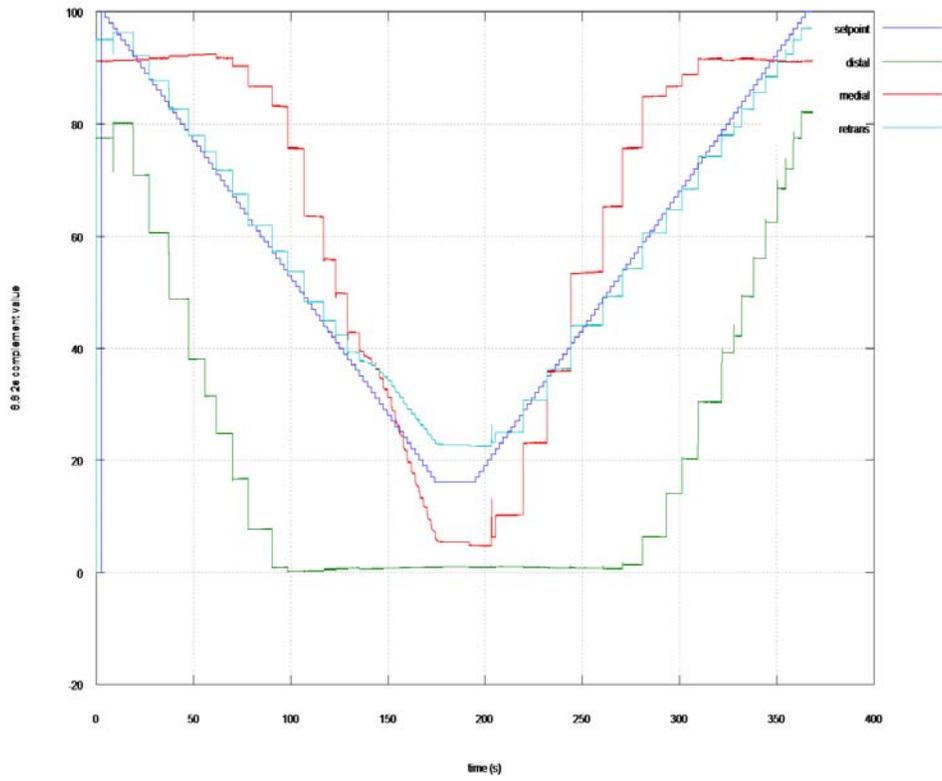


Figure 14: Ring Finger Response.

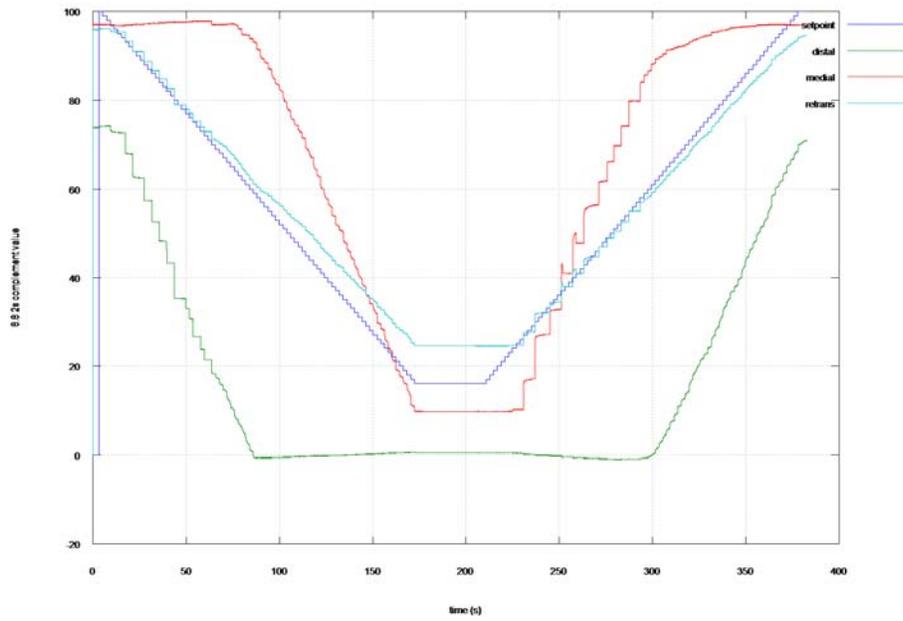


Figure 15: Pinky Finger Response.

In the final plot (Figure 16) we have modified the gains to emphasize the force control loop. In this plot the tracking is much closer and the positions have minimal steps, but the system now exhibits a high-frequency noise on the medial channel.

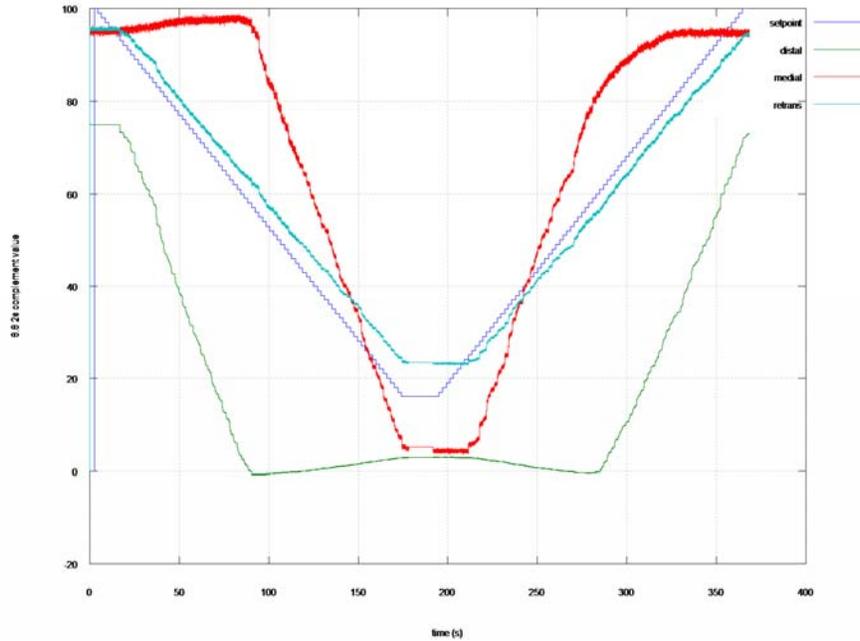


Figure 16: Middle Finger Response with Force Loop Gain Emphasis.

4.3 Shadow hand Interfacing Summary

Our efforts to improve tracking performance by tweaking gains were met with mixed results. The graphical representation that we developed for Shadowhand clearly showed that it could accurately track interface commands. In isolating that tracking problems it was clear that the Cyberglove was the major culprit. In our efforts to improve force control performance, however, we were less successful. It was possible to reduce position hops by increasing force gains, but this could result in unnecessary chatter and motor overheating. Ultimately this level of tuning should be left to the vendor. Based on our low-level efforts we are convinced the sensing system is adequate, but the motor control loop isn't.

5.0 OPERATOR INTERFACE DEVELOPMENT

An ideal hand controller would have the following features. It would work for any operator. It would allow the operator to both command position and force with precision, speed and accuracy. It would allow the operator to rapidly decouple and disconnect once a suitable grasp was obtained. It would be intuitive to use. It would be inexpensive and robust.

5.1 The Cyberglove

The Cyberglove system (Fig 17) has been a commercial product for grasping researchers for well over a decade, and has changed little over time. It computes hand position by measuring the flexing of embedded tendons. Ideally once a glove has been calibrated for a given user the flexing hand position can be directly converted to finger tip position. In practice this calibration is difficult to achieve, is laborious to perform, and can be corrupted simply by taking off the glove and putting it back on again.



Figure 17: Cyberglove System.

The Cyberglove is responsive and intuitive to use, but fails in most other categories. It does not work well for every operator. It does not measure accurately every joint, and the critical thumb motion is especially hard to control. There is no force feedback whatsoever for the operator, so the operator is left grasping at air, not knowing what level of contact is being commanded to the hand. The glove is expensive and somewhat fragile. The operator is also tethered into the system, and cannot perform other meaningful operations while they are thus constrained.

Due to the glove's inherent limitations for remote hand teleoperation, it was clear that we would need to pursue alternatives to achieve any viable operation of the system.

5.2 Force Feedback Exo-skeletons

The lack of force feedback and issues with tracking correspondance with gloves has long been recognized as a critical problem in hand control. The natural extension is to create a force feedback exo-skeleton system that monitors position and feeds back force. SARCOS research, NASA, and DLR have all developed exo-skeleton based force controllers for their respective hand designs. The Cybergrasp (<http://www.vrlogic.com/html/immersion/cybergrasp.html>) is the most typically cited “commercially” available system, albeit for over \$100K. Unfortunately, the feedback we’ve received from researchers that have used the Cybergrasp is that it was a failed attempt: expensive, fatiguing to the operators, unreliable, and intrusive.

To be effective an exo-skeleton design should be a kinematic replica of the slaved robot hand with the joint torque commands coupled tightly together. Since even obtaining good force information from the Shadowhand is still an issue, it is clear that a force-feedback exo-skeleton system was not an option.

5.3 The Finger Control box

In order to address the deficiencies of the cyberglove for teleoperation, we decided to take a different approach. The glove had no way to isolate either individual finger motion, or individual joints. It required continuous utilization of the operator’s hand, and did not decouple easily.

The finger control box, as shown in Figure 18 below was designed by us specifically for robot hand control. Like a game control console unit it uses “rate-mode” control, i.e., finger motion controls the speed of the joints, not the direct position. Unlike a game console that uses a pair of 2-DOF joysticks and no on-board display, we provided five rocker potentiometers, five LED displays, and a series of activation switches that could isolate control modes for operation.

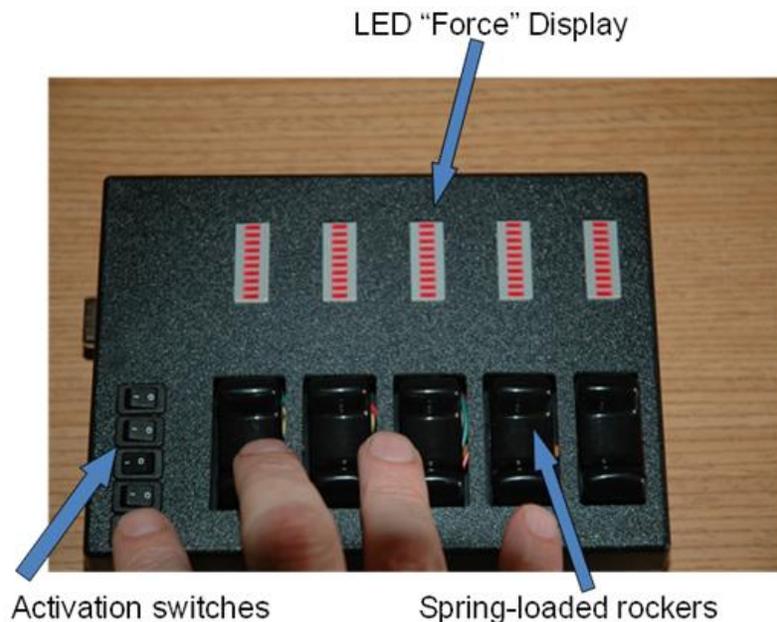


Figure 18: Finger Control Box.

The spring-loaded rocker switches give the operator a tactile sense of speed being commanded, while the force display gives them direct feedback about the forces for that command channel. Activation switches make it possible to isolate different fingers in performing an operation. To perform thumb and index finger only grasps for instance, simply turn off the switches for index, ring, and pinky fingers. An embedded micro controller processes the analog data from the rockers and digital settings from the switch locations and drives the LED display. It all couples to a PC controller using a simple RS-232 protocol.

The control box achieves many of our design objectives. It is responsive. It allows precision control of each finger tip. It is easy to decouple from it and move on to other tasks. The LED banks provide direct feedback of the force being exerted along a commanded direction. Additional software allows us to map the motion of the rockers to motions of the hand using numerous trial mappings. We developed finger tip based inverse kinematics mappings, and joint by joint control modes.

The hope was that through operation the hand control box would become intuitive for hand operations, in much the same way that a game console or a typewriter becomes intuitive. Namely, that if the system is tactile and comfortable, that an operator can generate a cognitive mapping through constant interaction, and that once constructed operation becomes second nature.

In reality, we never got that far in our operations with the finger box. With the hand's 24 degrees of freedom, it requires far more time than we had available to build up an intuitive mapping. All the optional methods of mapping from rockers to joints also made it hard to build up any consistent muscle memory.

The LED force display was informative, but ultimately we prefer to have the operator looking at remote camera feeds, and not at the control box. An improved design would incorporate tactile buzzers in the finger tips to designate the level of forces occurring in a channel. The hand control box continues to be a useful system for debugging the hand motion, but because of the time required to acquire an effective neural map it is not a likely candidate for a remote hand controller for IED operations.

5.4 Designing a finger tip tracker

The hand control box lacked the intuitive nature of the Cyberglove, and we realized there must be a better method for hand control. Our experience suggested that camera tracking systems could capture finger tip motion much more reliably than the glove, and without many of the drawbacks. Most importantly, the tracking systems would capture finger-to-finger opposition independent of hand size. Thus a handtracker system would be able to master the gist of the grasp without having to measure individual joint angles. The system we initially proposed is shown in Figure 19.

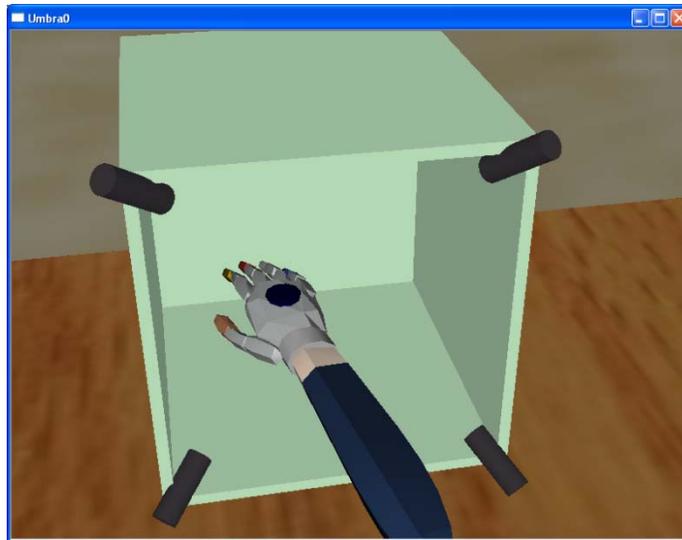


Figure 19: Proposed Hand Tracker

The system would use four USB cameras and monitor the finger tip and palm position of the operator's glove. Only two cameras would be needed to triangulate on any position. An inverse kinematics solver would then compute the kinematics to match the particular device, i.e., the ShadowHand. Four cameras would be used to minimize the impact of hand occlusion, and whenever more than two cameras were able to view a feature the accuracy would be improved.

Such a system could use inexpensive cameras (ours cost \$6each) but would require computing power to process the camera feeds. The Beagle board (Figure 20) would allow processing of two channels of live video, use less than a watt of power and cost less than \$200 each.

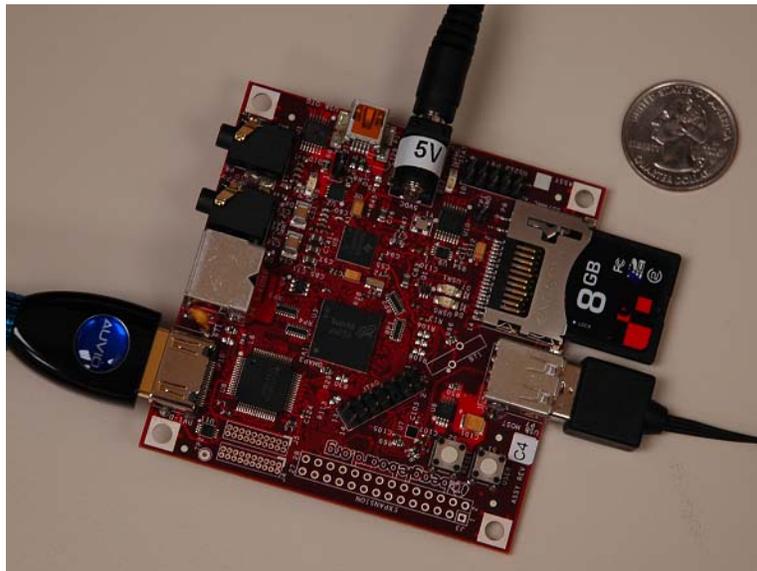


Figure 20: Beagle Board for Video Processing

To cut-down on table top clutter and to provide suitable standoff for the cameras we ultimately moved our design from a horizontal box to a vertical hole cut-out of a table. The bottom of the table is shown in Figure 21 below. An inverted skylight creates a fixed environment background



Figure 21: Hand Tracker Table

To calibrate the system, a vertical tower is placed inside the table as shown in Figure 22.

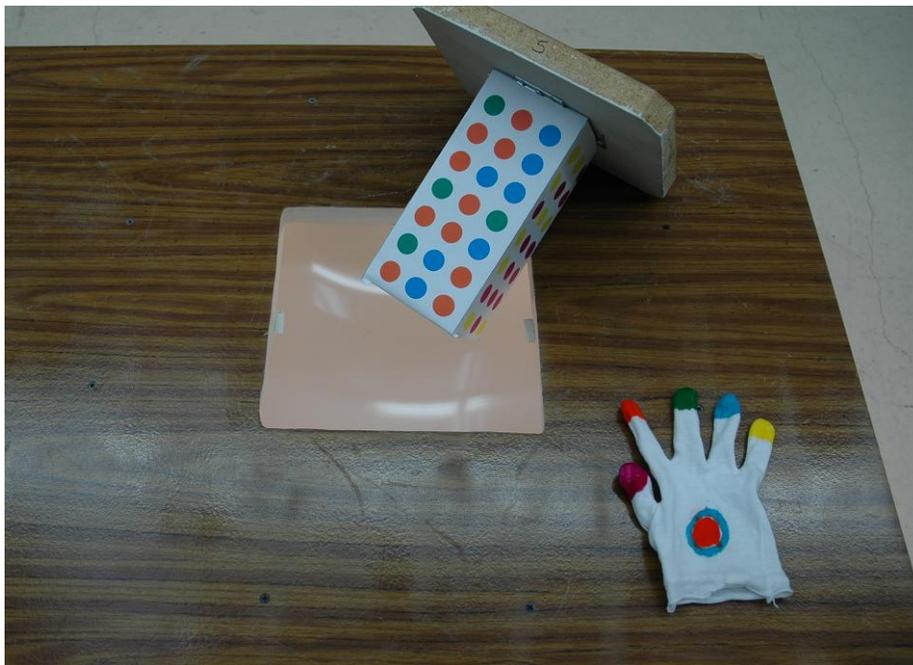


Figure 22: Calibration Tower and target glove used for hand tracker

The hand tracking system is implemented in Sandia's Umbra software system. By deploying existing software modules for attaching USB cameras, for image segmentation, for rapid region growing, and for color grid based calibration most of the pieces were already in place for implementing a glove based tracking system. Figure 23 shows the live video from one of the cameras underneath the table aimed at the calibration fixture. The second display shows the output of the segmentation module.



Figure 23: Input and output for color segmentation filter used for Hand Tracker.

The original color is sampled under various lighting conditions, and the regions that correspond to the desired region are grown to define convex color regions. For the glove we chose a five color system. Any pixel coming off of the camera that falls in the convex hull of one of the sampled colors is mapped to that color index, and the resulting regions of adjacent matches are then grown to create a color blob. Any other colors are mapped to a neutral gray. The use of a random color pattern makes finding and guaranteeing pattern correspondance automatic and fool-proof. The beauty of this approach is that it only requires a table look-up and a watershed based region growing algorithm to implement. It can be done at frame rate with minimal processing power.

Once cameras are calibrated the system is ready for glove tracking. The gloves are inexpensive inspector's gloves that have been colored with a set of markers. All sides of the finger tips are colored since the tracking system will need to triangulate on the center of the finger tip from any direction. Both the palm and the back of the palm are colored with concentric color feature. The combination provides another distinctive trackable feature. Figure 24 shows two of the four cameras being interpreted on a single CPU, and Figure 25 shows the same views from the calibrated camera perspective.



Figure 24: Glove tracking from a pair of cameras

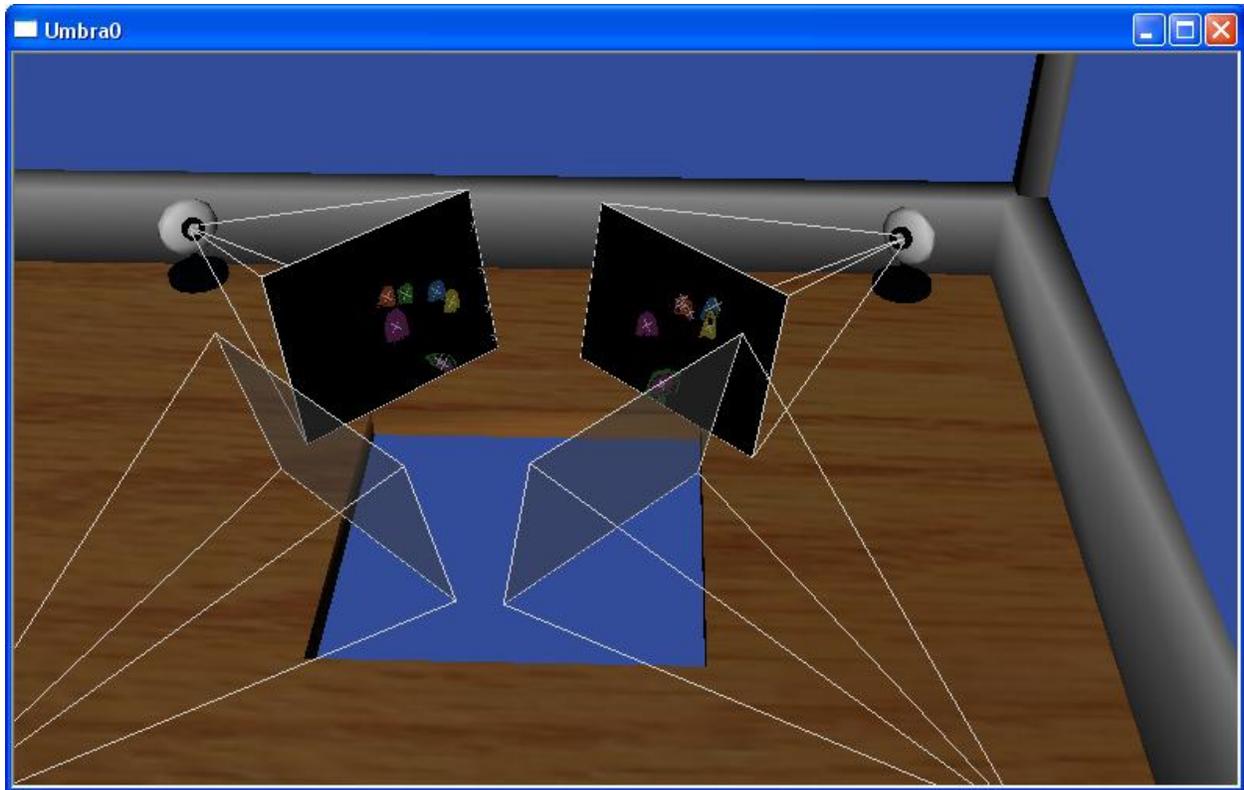


Figure 25: Calibrated camera perspective for glove tracking system

With finger tips and palm positions tracked in each camera view, triangulation is used to compute the relative positions between the finger tips and the palm. This data provides the input for an inverse kinematics solver that computes the joint angles for the particular grasper being commanded. In our case this will be the Shadowhand. The complete hand tracking system is still under development and will be completed in the spring of 2011.

5.5 The Xbox Kinect

In the winter of 2010, Microsoft introduced the Kinect system for the XBOX360 gaming system. The Kinect is an integrated camera system and time-of-flight range mapper for under \$200 that will revolutionize indoor robotics and man machine interfacing. Within twelve hours of release, software hackers had posted interface libraries, and since then there are numerous videos showing various interface uses of the Kinect, including “Minority Report interfaces”, virtual puppetry, etc.



Figure 26: The Microsoft Kinect

As an example, a MIT research group posted the video below showing the Kinect being used to duplicate the “Minority Report²” interface (<http://www.youtube.com/watch?v=tLschoMhuE>) Figure 26 below. The range mapping on the Kinect makes it far easier to segment out the fingertip motion from background clutter. The motion point cloud for the hands was deciphered using the MIT/WillowGarage Point Cloud Library (PCL). In this video the finger motions are mapped into a set of distinct gestures and used to control the interface to the screen.



Figure 27: “Minority Report” interfacing using a Kinect.

Robert Walter, a graduate student in Berlin has posted a number of hand tracking videos using the Kinect, such as the (Figure 27: <http://www.youtube.com/user/RobbeOfficial#p/a/u/1/ICuItHQEgEQ>). From the videos it is clear that the Kinect is completely suitable for tracking individual finger tips in real time.

² The Minority Report was a 2002 movie from Steven Spielberg starring Tom Cruise that demonstrated “futuristic” man-machine interfaces between humans and computers.



Figure 28Finger Tip tracking using the Kinect

The Kinect is probably the best interface choice for pursuing hand control interface development. It is inexpensive, robust, and appears to have the resolution and speed necessary needed to do the job.

It does have its limitations, however. It won't work in direct sunlight. Furthermore, a single Kinect system has no means for dealing with occlusion. Any fingers masked by the palm or each other cannot be detected. The kinematic library that was developed for gaming has focused on whole body motion and not hand motion – and that library is currently being kept under wraps by Microsoft. Other libraries exist, but in general mapping noisy point cloud data into precise skeletal motion is a difficult task.

The videos that have been posted show excellent fingertip tracking for hands with large finger tip separation or with pre-defined gestures. These are not the poses however someone would typically use for actual manipulation of objects. In conventional manipulation fingers are kept close together. These limitations, however, can all be overcome with research and algorithm development. The work that has been developed in posted in a single month of folks using this device is astounding.

5.6 Kinesthetic Feedback

Recreating force contact sensation has always been a goal for grasping research. Without feedback of force information to the operator it is difficult to understand whether an object is in a stable grasp position. Force information is critical for understanding whether an object can be moved, whether it is slipping, and whether if it is shifting in the hand. Numerous research efforts have attempted to recreate hand forces, but in general they can be considered expensive failures. Controllers using the exoskeleton approach such as the SARCOS and Cybergrasp are bulky, fatiguing to use, and because of their mechanical complexity difficult to maintain operationally.

The lowest cost, most robust solution for kinesthetic feedback is to embed vibrotactile devices inside of a glove. Unfortunately these can't convey direct force, but only provide vibratory "hints" that contact is occurring. The Cybertouch (<http://www.cyberglovesystems.com/products/cybertouch/overview>) is an example of a commercial device that can be used to provide vibrotactile feedback with six different actuators. At \$15K it is expensive, and provides only finger tip and palm contact info, not full finger surface contact.

5.7 Interface Recommendations

During the last year we have investigated multiple options for controlling the Shadowhand. The initial Cyberglove does not appear to be a viable choice. Besides being expensive, it fails to give accurate relative finger tip measurements needed for precise control, and tethers the operators hand to a work station.

Deciding to explore other options, we developed and experimented with both a rate mode hand controller and a camera based visual tracking system. The rate-mode system was not as intuitive to use as we had hoped for, and the camera based system although promising requires far more development to prove its worth.

The introduction of the Kinect as a new innovative piece of hardware paves the way for a new generation of man-machine interfacing. Although it does not provide the critical contact information needed for grasping, we believe that by combining one or more of visual queues and low-cost tactile vibrators, an intuitive, robust, solution can be developed for remote operation of robotic hands such as the Shadowhand.

6.0 THE ROBOT TESTBEDS

As part of this trial evaluation two IED robot platforms were provided. A Foster-Miller Talon vehicle and a research version of the Northrop Grumman Cutlass manipulator arm. We were tasked to interface the hand to both of these platforms and evaluate the resulting systems.

6.1 The Talon/Shadowhand testbed

The Foster-Miller Talon vehicle (http://en.wikipedia.org/wiki/Foster-Miller_TALON) represents perhaps the most successfully IED robot in combat operations. Thousands of these vehicles have been built and deployed, and most military bombsquad units are intimately familiar with its capabilities. It is fast, rugged, and can carry numerous payloads. It can be two-man lifted and has a long battery life.

Its design was motivated by the roadside IED threat – which typically requires reconnaissance and only minimal manipulation. Typical tasks include placing a counter charge and dragging trashbags in rubble piles. Its deployed gripper is nothing more than a simple pincher grip. The manipulator itself has only four degrees-of-freedom: a rotating torso, and shoulder and elbow pitch (actuated from a four-bar-linkage), and a wrist roll. It lacks the minimal six-DOFs required for placing a rigid body into any arbitrary pose. By reducing degrees-of-freedom and keeping a simple gripper, the designers have been able to focus on the mission needs: keep it simple, keep it light and fast, and keep it robust. Unfortunately, this design philosophy doesn't provide a good starting platform for dexterous manipulation.

The ShadowHand itself can provide some of this missing motion by using its wrist actuators. The Talon wrist can neither pitch nor yaw, but the hand can. Unfortunately this only gives a minimal range of motion (+14 to 17 degrees pitch, and -20 to 20 degrees yaw). This is insufficient for providing the arm positioning needed for most advanced manipulation tasks.

Our Talon-Shadowhand integrated system is shown in Figure 28. Only a few modifications were needed to support this work. A tool interface plate was designed and fabricated to allow rapid mounting of the Shadowhand onto Talon, and an E-stop system was added to allow operations within Sandia's Standard Operating Procedure for Robots.

The mast-camera on board the Talon provided the only reasonable view of Talon during operations. With its full-color, PTU and zoom capabilities it provided a good view of manipulation for tasks at ground-level, but was mostly occluded when performing tasks in front of the hand.

Manipulation of the Talon was via the conventional joint-by-joint joystick controls provided by the Talon console. With this type of interface, inadvertent motions are common for a novice operator, and our operators had considerable trepidation that they would damage the expensive Shadowhand during testing. Because of its exposed location the Shadowhand would be the first thing to collide with a wall or object when driving, and due to poor depth perception from the single camera view it would be easy to drive the hand into the floor without being immediately aware of it.

The Talon control interface/arm combination lacks many of the features needed for advanced dexterous manipulation. No automatic camera tracking. No self-awareness of position, insignificant DOFs for rigid body motion, and no straight-line motion capability. Perhaps more importantly, it lacks any joint level force control making it very difficult for the precision hand to survive the operator, much less an IED.

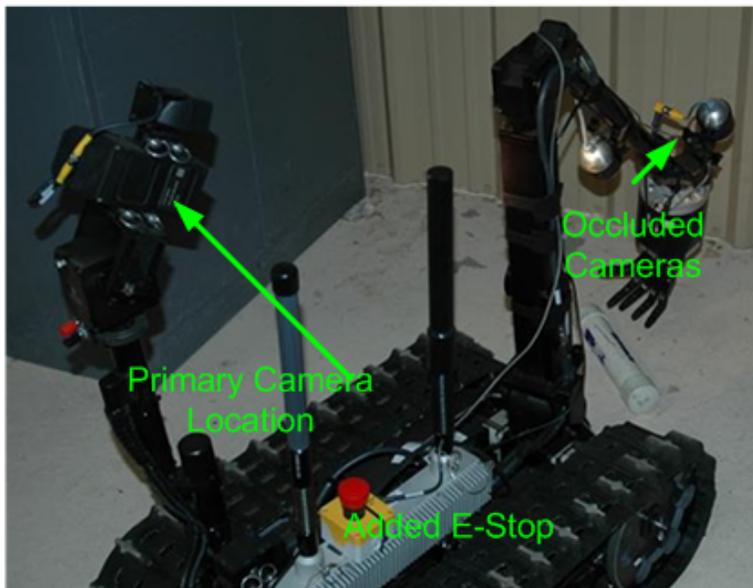
The Talon Control Console



Console View Closeup



Talon With Shadow Hand Mounted



Hand-Mount Closeup

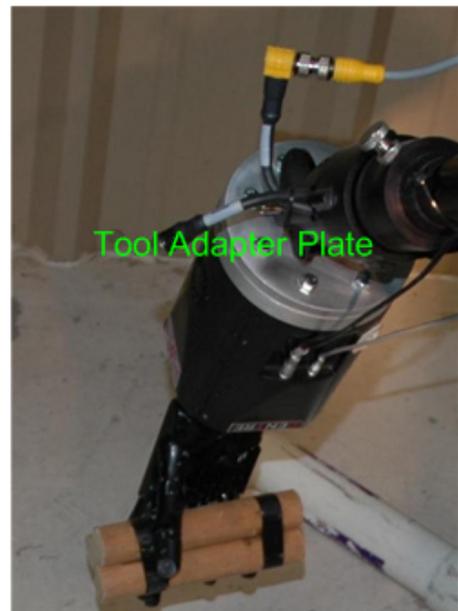


Figure 29: Talon-Shadowhand Testbed

6.2 Running the ShadowHand on Cutlass

The Nortrop-Grumman Culass platform represents the other side of the spectrum for IEDD-focused manipulation. It has three times the reach, more than double the degrees-of-freedom, a sophisticated wrist tool change out system, and numerous camera locations. It was designed for difficult car entry problems in an urban environment with a heavy focus on manipulation. The nine joints not only allow full position and orientation of grasped objects, the redundancy allows the arm to perform these tasks in a constrained and cluttered environment.

Although the military versions of this platform have not yet been provided to operators as of Dec. 2010, we were able to perform evaluations of this system using an Advanced Demonstrator Unit prototype of the Cutlass with a custom Sandia-developed control interface. This demonstrator unit is shown in Figure 29 below, and has been outfitted with Sandia's visual targeting software. Three high-speed calibrated color zoom cameras are available to the operator in addition to the conventional weapon and drive cameras locations.

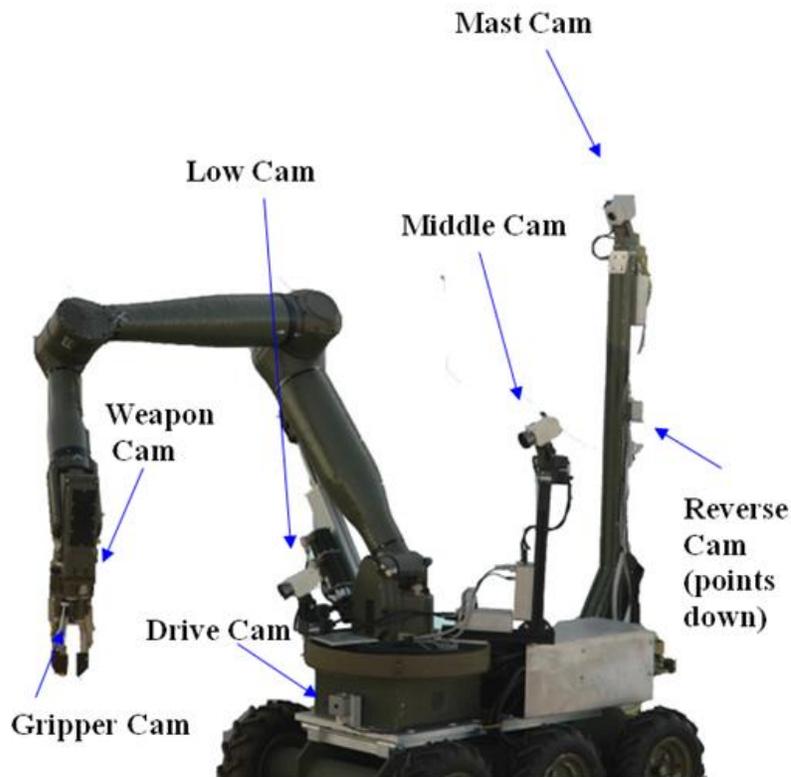


Figure 30: Cutlass Advanced Demonstrator with Targeting Cameras

The integrated ShadowHand system is shown in Figure 30, and the controller console for the system is shown in Figures 31 and 32:

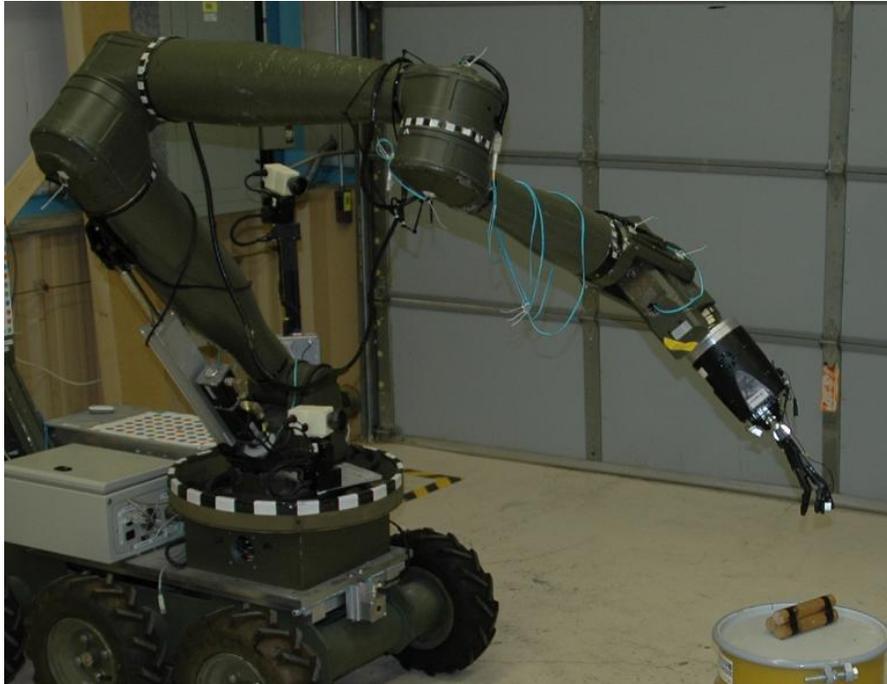


Figure 31: Integrated Cutlass/ShadowHand System



Figure 32: Operator Controls for Cutlass Demonstrator

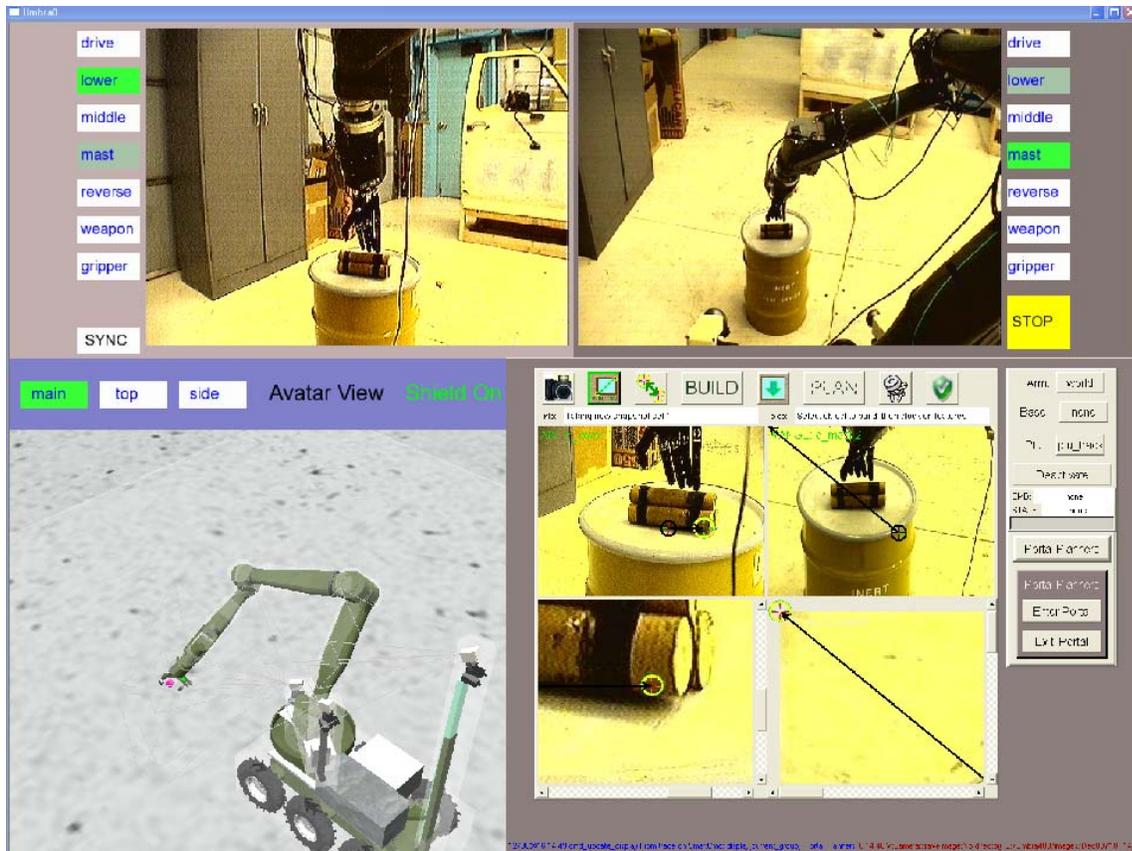


Figure 33: Sandia Developed Operator GUI for Cutlass Demonstrator Unit

The Cutlass controller offers many advantages over the Talon system. The control of the arm is fundamentally straight-line, with separate control channels for commanding translation, pitch, yaw and roll. Inadvertent operator motion is far less likely when using the Cutlass arm.

Eight different cameras and touch screen selection of cameras makes camera visualization a lot easier. With the redundant joints available on Cutlass the arm's links can be kept out of the camera line-of-sight, providing unobstructed views of the robot hand. Ten-fold analog zoom and automated camera tracking substantially reduce the burden of maintaining good views of the target.

The Shadowhand base height still prevents optimal wrist pitch and yaw. The base of the hand is staggered some 30 centimeters away from the center of rotation of the cutlass wrist, so although Cutlass can provide wrist yaw and wrist pitch to complement the minimal pitch/yaw available from the Shadowhand, it is pivoting from a human forearm's distance away. This hinders access in most tight spaces, and is highly non-anthropomorphic.

In addition, the Cutlass system suffers from the same primary problem that Talon suffers from. There is no force sensing and no force awareness. It is too easy for the operator to severely damage the hand, and the system has no inherent means to detect or mitigate high forces on contact. The arm motion on Cutlass may be much more precise than on Talon, but both vehicles use a skid-steer base. The greater reach and power of Cutlass amplifies the potential damage when executing a skid-turn into a rigid object.

The combination of no force control sensing on hand, no force/torque control on arm, no innate collision modeling, and crude skid-steer driving results is a recipe for broken hands and failed missions.

6.3 ShadowHand Camera Systems

Typically, a device such as the Shadowhand is controlled within direct line of sight of the operator, who is typically no more than a few feet away. The operator is free to move around the hand and get a clear view of any object they are attempting to grasp

For an IED robot operator, however, the situation is completely different. Typically the robot arm would be operated behind a building, without any direct line of sight, and totally based on camera views. Because most robot cameras are attached to the robot frame and forearm these cameras can be easily occluded by the base of the Shadowhand.



Figure 34: ShadowHand Camera Locations.

In order to complement camera systems from the robot we experimented with two hand mounted camera locations: one on a finger tip, and one in the palm (Figure 33).

The fingertip camera was not used to aid in grasping, but to extend the functionality of the hand for surveillance in tight quarters. Having a camera that can look into tight crevases and containers on a flexible finger tip can be extremely useful for an IED operator. Although our installed cameras were small, ideally an even smaller endoscope camera could be deployed in a similar position.

The palm camera was designed to help the operator align with objects for grasps. Once objects were grasped, however, it was typically occluded by the grasped object and its usefulness was diminished.

6.4 Arm Testbed Conclusions

Neither the Talon nor the Cutlass provides a viable platform for deploying the Shadowhand for IED operations. Without additional safety measures such as force control and collision sensing, the hand would inevitably devolve into a twisted bundle of tendons and dangling finger tips. Cutlass does provide the reach and the degrees-of-freedom required to properly deploy the hand into useful poses, but unless tightly integrated into hand operations it is difficult to control as a system. Even then, the long stand-off base required to power and operate the shadowhand restricts its utility.

In our opinion the combination of hand and arm combination being issued by DARPA for their dexterous manipulation initiative is far more appropriate and balanced. The Barrett Arm is a seven –DOF arm that was designed for contact operations. Its light weight and tendon based control minimizes contact forces and allows direct mitigation of closed chain forces. The Barrett hand is far simpler with only 4 actuators, but can achieve far greater surety of grasping than the Shadowhand. Its compact base ensures a tightly coupled yaw/pitch location, and its greater power and finger tip length can better envelop objects.

7.0 RECOMMENDATIONS FOR FUTURE DEVELOPMENT

In this report we have given a brief history of robot hand development, described our experience with using the Shadowhand with the provided Cyberglove interface, gave details about the inner workings of the Shadowhand system and documented our efforts to understand its servo performance and limitations, described designs to improve operator interfacing to the Shadowhand, and finally discussed how Shadowhand could be interfaced onto two mobile manipulator platforms.

The Shadowhand has proven surprisingly reliable during our testing stages, and has clearly improved upon robot hand designs of the past. The positioning and force sensor systems are clever and well implemented. The Shadowhand is definitely a fascinating piece of hardware, but it is not close to being ready for deployment as an effective tool for IEDD operations.

First, the Shadowhand electronics need to be improved substantially. Without viable control of closure forces and sub-degree positioning accuracy the hand is not viable as a grasping tool. The current CAN-bus internal communications is insufficient to meet the high-speed bandwidth requirements for advanced servoing algorithms. Adaptive friction compensation and gain scheduling approaches should be considered to deal with the high-level of friction variability over the motion space. The force levels that the hand can provide also need to be increased. Currently the grip is weak, and it is unable to hold even a simple power drill.

Second, the interfacing needs to be improved. The Cyberglove as an interface device is ineffective. Without precise finger-tip tracking and a means to convey kinesthetic information the operator cannot effectively command motions of the hand. Although we pursued two possible alternatives, a rate mode control switchbox and a four camera hand tracker system, we believe the best current approach is to investigate Kinect based tracking solutions. Kinesthetic feedback could be conveyed with either visual queues or with vibro tactile devices.

Third, the interface to a robot must be done from the outset, not just attached to the end of an existing arm. The effectiveness of the hand depends on the effectiveness of the wrist and arm that precedes it. To even consider deploying a complex and expensive tool such as the Shadowhand there must be a means to protect the hardware from inadvertent mishaps. Force control and better workspace sensing technologies need to be developed to better guide operations of the hand. For effective kinematics the center wrist of the hand should coincide with the gimbal center of the robot's wrist. Human visualization for dexterous operations depends on a vision system that operates in close proximity to a target. The robot's visual acuity system needs to be designed to match it.

Although the human-hand is an intriguing device, recreating it for remote robotic operations is a difficult endeavor. Recreating the look of a human hand, as Shadowhand has done, is not the same thing as recreating the functional capability of the hand. Simple parallel jaw grippers with concave features on their finger tips already provide rock-solid multi-contact grasps for many objects. The Barrett Hand provides numerous grasp options using only four-motors. Any new design will have to provide functionality that exceeds these examples. IEDD operators deserve

the most capable systems engineers can provide to do their work, hopefully through the efforts of innovative companies like ShadowRobot; we can provide them the tools they need.

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