RoboGlove – A Grasp Assist Device for Earth and Space

M. A. Diftler*, C. A. Ihrke**, L. B. Bridgwater*, J. M. Rogers*,
D. R. Davis**, D. M. Linn**, E. A. Laske*, K. G. Ensley*, J. H. Lee*

*NASA/JSC, Houston, Texas
**General Motors, Warren, Michigan

Abstract*— The RoboGlove is an assistive device that can augment human strength, endurance or provide directed motion for use in rehabilitation. RoboGlove is a spinoff of the highly successful Robonaut 2 (R2) system developed as part of a partnership between General Motors and NASA. This extremely lightweight device employs an actuator system based on the R2 finger drive system to transfer part or the entire grasp load from human tendons to artificial ones contained in the glove. Steady state loads ranging from 15 to 20 lbs. and peaks approaching 50 lbs. are achievable. Work is underway to integrate the RoboGlove system with a space suit glove to add strength or reduce fatigue during spacewalks. Tactile sensing, miniaturized electronics, and on-board processing provide sufficient flexibility for applications in many industries. The following describes the design, mechanical/electrical integration, and control features of the glove in an assembly-line configuration and discusses work toward the space suit application.

I. Introduction

IN 2007, NASA and General Motors began the development of Robonaut 2 (R2) [1,2], a humanoid robot designed to do human scale work. The requirements for human scale work include grasping hands with superior machine dexterity and object manipulation capabilities. The considerable challenge of developing such a highly capable robotic machine resulted in the development of many independent novel technologies, which were then integrated into the final R2 robot. In the flurry of innovative creativity developing R2, it was recognized that many of these technologies could be reconfigured and applied to other mechanisms and applications – so called "spin-offs" of the R2 development. It was during the testing of the R2 tendon based actuator system [3,4] that the idea to apply this technology to a human-worn glove device was conceived.

RoboGlove, like R2 itself, is a device for assisting people by interacting directly with human interfaces. In this case, the glove augments the human's capability with minimum restriction by applying forces in parallel with the fingers and thumb. This is a variation on a technique that has been used in several fields including robotics to provide force feedback, contact information, tactile feedback, increased grasp strength and rehabilitative motions.

A number of devices, both commercial and prototype, apply forces directly to the human hand providing information on a remote or simulated environment. The CyberTouch [5] uses small motors to generate forces on the back of fingers indicating contact. The CyberGrasp [5] uses an exoskeleton to actively resist human finger motion. The Magic Glove [6] uses a related technique by sensing the human's contact force with an object and converting that to a command for a robot, also in contract with the object, to move the object.

Many researchers have pursued grasp assist gloves for use in rehabilitation and in some cases as a more permanent aid to help with activities of daily living. A pneumatic glove from Okayama University provides assistance with an innovative rubber muscle [7]. The PneuGlove shows promise in helping stroke victims regain capability when used during rehabilitation in an "assist as needed" mode during hand motions [8]. Toshiba's Power Assist Glove system predicts the intent of the user in order to achieve the desired grasp [9].

Work with non-pneumatic devices is also underway. The innovative SEM Glove provides a moderate amount of extra grip strength in a modular package [10]. The College of New Jersey is developing a hand exoskeleton using linear actuators and mechanical cables to provide much higher grip strengths [11]. Efforts to provide a space suit glove with power-assistance have been attempted at the University of Maryland Space Systems Laboratory using a single actuator and Spectra cable [12].

Fig 1. The GM/NASA RoboGlove

Designed with substantial grip forces as a primary requirement, the current version of RoboGlove focuses on high peak loads and endurance for significant steady state loads in a comfortable, lightweight package. The initial targeted applications for the RoboGlove are augmented space suit gloves and repetitive assembly line tasks, but other opportunities are continuing to present themselves.

Any application where significant grasp forces are needed is a candidate for this technology. In addition to the devices noted above, a variant on the RoboGlove holds potential in rehabilitation and even prosthetics.

Like any attempt to recreate the subtleties of human capabilities, in this case, finger motion and grasping, RoboGlove is a work in progress. The following describes: design philosophy, mechanism design, sensing, avionics, control, initial testing, and future development.

II. BUILDING ON R2'S DESIGN

The RoboGlove (Figure 1) follows key elements of Robonaut 2 (R2)'s hand design approach, including tendon actuation, distributed controls, and localized tactile sensing.

RoboGlove shares features of the patented Tendon Driven Finger Actuation System technology that was developed for R2 [4]. The same linear actuation concept consisting of small brushless DC servomotors coupled with small ball screws is used. However, since it is designed to augment grasping force and not to control the position of the user's fingers, RoboGlove requires only a single tendon for each finger. In comparison, Robonaut's primary fingers and thumb require 4 and 5 tendons respectively to control all of the independent degrees of freedom.

RoboGlove follows R2's approach of locating the actuators and electronics as close as practical to the point of operation. For RoboGlove, this means that the linear actuators, the drive electronics, and the microprocessor are all contained within the forearm section of the glove. To be comfortable for the user, miniaturization of components and the use of lightweight materials were important considerations.

RoboGlove also shares the concept of localized tactile force sensing with R2. RoboGlove's requirements for tactile force resolution are less stringent than R2's, for example, only a single force direction is needed. However the space available for sensors is even more limited in RoboGlove than R2. Therefore a commercial thin film piezoresistive force sensor used in earlier Robonaut work [13] was selected for the RoboGlove, compared with custom six axis load cells for R2 [4].

III. MECHANISM

A. Overview

In the human hand, the flexor digitorum profundus and flexor pollicis longus muscles actuate tendons that close the fingers and thumb. RoboGlove uses electromechanical actuators and artificial tendons in parallel with the human system to reduce the forces required by the muscles during certain repeated and/or prolonged grasping tasks.

Three linear actuators located extrinsically on the palmar section of the forearm of RoboGlove actuate tendons that flex all five fingers of the user's hand. By assisting all five fingers, RoboGlove can exert up to approximately 50 lbs. of grasp force momentarily, while providing a continuous grasp of approximately 15-20 lbs.

Most of RoboGlove is fabricated from flexible, elastic fabric material in order to conform to the user's forearm and hand, minimize weight, and minimize any reduction in the dexterity of the user. The palmar side of RoboGlove incorporates high friction materials in order to assist holding a grasp on a wide variety of object surfaces. RoboGlove's soft goods provide a durable structure to protect the user and contain all of RoboGlove's mechatronics.

RoboGlove weighs approximately 1.7 lbs. and is available in three different sizes to accommodate variations in hand sizes of the general population. In addition to having three different glove sizes available, zippered sizing bands along the forearm and Velcro wrist straps allow for simple adjustments to accommodate a wide range of users.

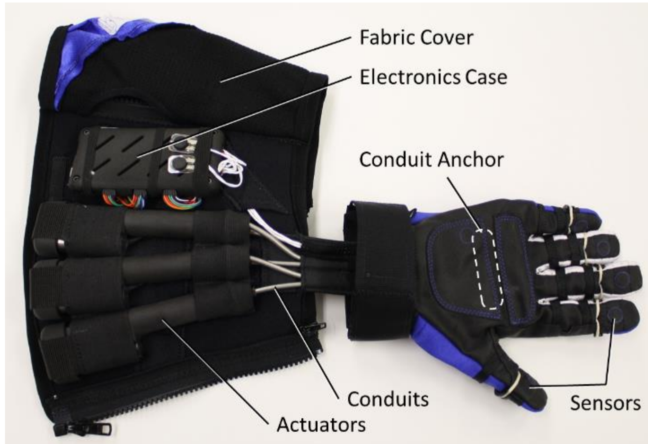

Fig. 2. Forearm Layout, Conduit Anchor, and Sensors

B. Finger/Palm Interface

Each finger tendon in RoboGlove is routed from a linear actuator located in the forearm section of the glove across the wrist inside a flexible conduit (Figure 2). The conduit reacts the tendon load, which thereby prevents the tendon from exerting a force or moment across the user's wrist. The conduit terminates in a rigid anchor embedded within the palmar half of the glove, proximal to the metacarpal interphalangeal joints of the fingers. After the conduit anchor, the tendon continues along the palm side of the finger to its termination at the medial phalange (in the case of a finger) or the distal phalange (in the case of the thumb) of the user's digit.

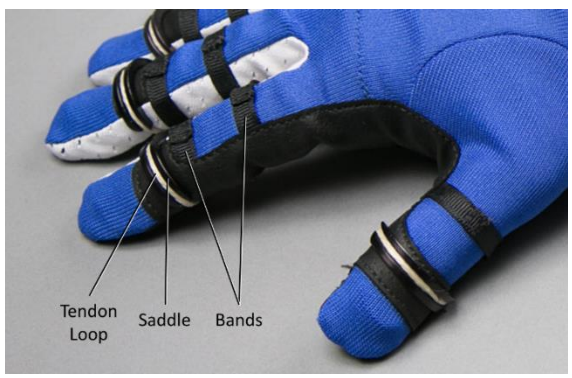

Fig. 3. Finger Detail

Termination of the RoboGlove tendon at the medial or distal phalange is completed by means of an eye-splice that loops around the dorsal side of the user's finger (Figure 3). A rigid saddle is used to distribute the force from the tendon evenly and to prevent cinching of the loop around the finger. Additional inelastic fabric bands on the proximal and medial phalanges keep the tendon routed close to the finger during grasping and also help transmit tendon force to the dorsal side of the user's finger.

C. *Drive train*

RoboGlove's actuation system is a derivative of R2's finger actuator technology [3] with some key changes. A longer ball-screw assembly is implemented to gain extra travel in order to fully flex the user's fingers. The motors are relocated to minimize the length of the actuators along the forearm. Internal guide rails, rather than a guide pin, allow the system to be completely enclosed to minimize the intrusion of debris. The motor gearhead ratio is reduced to increase the speed of actuation to better match that of the human operator, as well as to provide emergency backdrivability of the drivetrain. A sliding tendon hook is implemented to allow for differentiation in the grasp shape of mutually actuated fingers. A cross section of the RoboGlove actuator is shown in Figure 4.

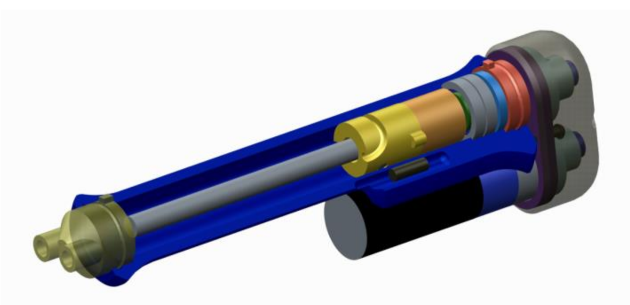

Fig. 4. Linear actuator in cross-section

IV. AVIONICS AND CONTROLLERS

The forearm section of the glove contains all the power, control, and drive electronics required for glove operation. These electronics are contained within a ruggedized case. (Figure 2).

A. *Main Controller*

The electronics on RoboGlove are condensed onto a single circuit board called Cerberus. (Figure 5.) The board is powered directly from the battery pack, drives the motors with raw battery voltage, and converts this voltage to power all logic and control circuitry. Cerberus includes a microcontroller (MCU) communicating with an FPGA, configured as a central communications hub, through a point-to-point serial link. The FPGA manages sensor analog to digital conversion, temperature sensor measurement, actuator encoder accumulation, and motor commutation and control signals. The MCU manages the control loops from data provided by the FPGA, manages the various control modes depending on the sensor inputs, and communicates information back to the user through the LED interface.

B. *Motor Drivers*

Motor drive technology has advanced considerably in recent years. The development path that led to R2's hand motor control boards [4] started in the late 1990's and was designed with space applications in mind. Though well suited for R2 space operations, the large and expensive motor driver hybrid circuits were not applicable to the small, inexpensive, low-power requirements for RoboGlove.

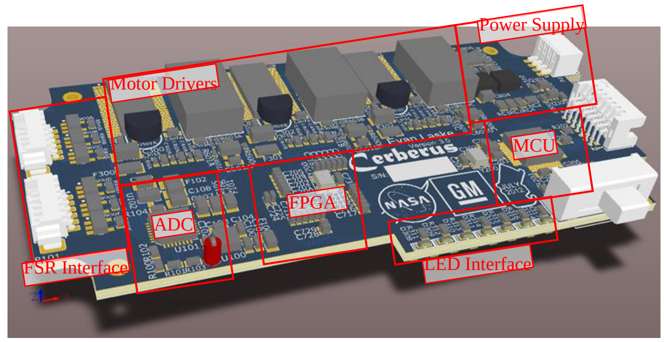

Fig. 5. Cerberus board overview.

Instead, the RoboGlove development focused on utilizing commercially-available integrated motor drivers. This enabled the custom hybrid circuit to be replaced with off-the-shelf components resulting in a reduction in size. The reduction in size subsequently enabled the inclusion of all of the upstream control electronics and sensor interfaces into the latest generation Cerberus board. Even after combining the entire electrical and control system onto a single board, the board and corresponding ruggedized case now has a smaller volume and half the weight of an iPhone.

C. *Sensing*

In order to have better insight into the operation of the motors, the current to each motor is sensed. The MCU uses this motor current information to provide coarse, open-loop control of the glove's applied force through closed-loop current control of the motors. In addition, the battery voltage and current are sensed. After characterization of the battery, this voltage and current information gives an accurate estimation of how much charge is left within the battery and can alert the operator when a low charge requires battery replacement.

For feedback of the output force at the point of contact with the user's environment, thin film piezoresistive force sensitive resistors (FSRs) are used. The sensors are embedded in the glove's fingertips as illustrated above in Figure 2. This type of sensor changes resistance inversely proportional to the force applied.

$$R_s \propto \frac{1}{F}$$

Interface circuitry (Figure 6) on the Cerberus board linearizes the response of the sensor by varying the gain on a constant-voltage excitation signal. This gain varies inversely proportional to the sensor's resistance.

$$V_{out} = -V_T \left(\frac{R_f}{R_s}\right)$$

Combined, this gives a direct proportional relationship between force applied and voltage output.

$$V_{out} = -V_T R_f k F$$

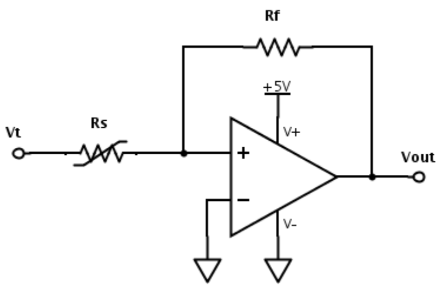

Fig. 6. FSR interface circuit.

In addition to the application in force control, these sensors are used as human interaction inputs for defining control states. Thresholds are set for each of the FSRs, depending on the mode of operation, to trigger specific actions. Similarly, electromyographic sensors have been explored for triggering certain glove actions, such as closing and opening the grasp. These could potentially be integrated as a complementary sensing device to the FSRs or as a replacement if finer force control is not needed.

D. *Interface*

The RoboGlove has a simple but intuitive user interface. The control module contains a three position switch that allows the user to select the mode of operation depending on the task. LED's display information about the state of the glove. One LED communicates that the glove is powered, while other LEDs are programmable to indicate the state of the sensors or actuators, the control mode, faults, etc. Typically, the LEDs give feedback about actuator position, the control mode, and faults that are detected. For additional information about the state of the glove, blinking patterns can be programmed, for example if a specific fault is detected.

The control module contains an external interface port for use in programming, troubleshooting, and calibration. When plugged into a computer, this external interface can also be used to stream sensor data and debugging parameters to a terminal or calibration software.

V. CONTROL

As described above, the FPGA gathers data from the sensors and commutates the motors, making all data available to the MCU through a point-to-point serial link. The MCU is responsible for closing all control loops and interfacing with the user. This separation was implemented to optimize operation by utilizing the advantages of each type of chip. The FPGA can gather data from multiple sensors in parallel, whereas the MCU has high-resolution PWM peripherals and can be programmed and developed quickly in C.

A. *Operation*

At power-up, the RoboGlove slowly runs the actuators fully open and sets soft limits and zones in the actuator space based on the encoder data. During operation, these soft limits and zones are used to prevent the actuators from reaching the end of travel and to detect other off-nominal states. When the actuator approaches the physical limits, it passes through a control-magnitude limited zone where the maximum motor command is limited. If the actuator continues and encounters a soft limit, the motor command is zeroed.

After initial setup, RoboGlove's operation depends on the mode selected. A typical operational mode will operate the glove in the following manner: close the glove if the index finger FSR exceeds a certain force threshold and open when the FSR drops below that threshold. In this example, a tool could be grasped in the user's hand; the glove would be actuated by pressing with the index finger to exceed the FSR threshold; then the tool would be held by the glove's tendons. When the user wishes to release the tool, he or she opens the index fingertip slightly, lowering the net applied force of the glove, as seen by the FSR, below the programmed threshold.

In this case, the FSR is essentially used as an on/off switch, enabling the glove to augment the user's grasp. Other modes can utilize the FSRs as force-feedback sensors, for example to control the combined user/RoboGlove grasp force, or to offload the grasp force completely from the user, allowing the user to relax within the glove.

B. *Algorithms*

Different internal control algorithms are used depending on the current operational mode of the glove. In the example above, a constant motor command is used. In a force-control mode, the current data and FSR data are used as coarse and fine force feedback inputs controlling the motor command. Velocity of the actuator is used to adjust the motor commands in order to achieve the holding force required. As the velocity drops to zero, the motor command required to hold the grasp can be lowered as well due to the additional holding force provided by the internal static friction of the actuation system.

C. *Safety*

Given that RoboGlove is designed to be worn by a human user, the safety of the device is critical. While the glove is in operation, the MCU monitors the overall status of the system. If any off-nominal operation is detected, RoboGlove will automatically open completely and cease actuation. The LEDs will alert the operator of a fault and indicate which type of fault has occurred. For example, high motor temperature, high battery temperature, high motor current, low battery voltage, or loss of sensor feedback are conditions that will result in a faulted state of the glove.

Mechanical safety features included backdrivability of the drivetrain when the power is removed and the ability to unzip the glove and remove the user's hand if operation fails in an abnormal position.

VI. APPLICATIONS

As with R2, the design intent for RoboGlove was to provide the user with enhanced ability to perform human scale work, with considerations for speed, power, durability and dexterity. The glove assists the user by providing additional hand grasp strength, which reduces strain and fatigue. The need to provide additional hand grasp strength is seen in a wide range of areas, from medical rehabilitation and prosthetics to construction, manufacturing, and assisting humans operating in constrained environments, such as in space or underwater.

General Motors is considering a variety of applications in automotive assembly. The best candidates are tasks that are ergonomically challenging, require strenuous grasps, momentarily high grasp forces, or repetitive grasping. Examples include: moving heavy objects with difficult hand holds, repositioning an object with wrist motion while maintaining a tight grasp, holding a power tool for an extended duration, or repetitively snapping components together during assembly.

Through the High Performance EVA Glove project, NASA is working to improve function and fit of space suit gloves for the future [14]. RoboGlove technology is an excellent candidate to help in the pursuit of superior designs for what is one of the most challenging parts of a space suit. Astronauts must fight the differential between suit pressure and vacuum to move their fingers and adjust grasps. Work is underway to integrate the RoboGlove into a Phase VI space suit glove. This initial effort uses the RoboGlove actuation system described above while making minor modifications to the suit glove's structural layer and outer Thermal Micrometeoroid Garment (TMG). As of the publication of this paper, a prototype of the assisted glove is being tested in a depressurized glove box at the Johnson Space Center.

Fig. 7. Early prototype for RoboGlove integration with a space suit glove

Many opportunities exist beyond the current General Motors and NASA applications. Glove boxes used for work with hazardous materials could incorporate RoboGlove technology to alleviate user fatigue or to perform more physically demanding tasks. Similar challenges exist in the nuclear/chemical industry where very thick gloves designed to protect the user are excessively restrictive and difficult to manipulate. Any industry that employs large tools or ones with a high grasp force is a good candidate. Not surprisingly, the application list is extensive.

VII. INITIAL TESTING

Initial application trials of RoboGlove were conducted in the assembly of prototype vehicles at the General Motors Technical Center in Warren, Michigan. Trial applications were selected based on ergonomic difficulty as well as suitability for RoboGlove. Several applications were attempted, two of which are described here. Trials were performed by users familiar with the operations performed.

A. *Wire Harness Crimping*

Wire harnesses are assembled manually for use in prototype vehicles. Terminals are crimped onto the ends of each wire in the harness, in the numbers of hundreds of crimps per vehicle. The task is physically demanding in both the grasp force required and in repetitiveness.

Using a grip force dynamometer, it was estimated that a typical automotive wire harness crimp requires between 40 and 90 pounds of grasping force depending on the size of the wire terminal. For this application, RoboGlove was programmed to maximize peak force over a short time duration. The algorithm used fingertip sensor input to command the gripping action, and actuator velocity to determine when the grasp had been completed. After the grasp was completed, the control program reduced the current to the motors to avoid overheating, but maintained the grasp until the fingertip sensors were released. By this method, a peak grip force exceeding 40 pounds was achieved. This force is additive to the user's own grasping effort. RoboGlove was able to significantly reduce the amount of grip force the user is required to provide for this operation.

Fig. 8. Crimping operation (illustration only)

B. *Door Glass Install*

Side door glass is installed manually in both prototype and production vehicles. The glass is held between the operator's four fingers and palm of the hand, i.e. a four-fingered grasp. The operator typically carries the majority of the weight of the glass with one hand while performing fine manipulation and other dexterous actions with the other hand. Therefore, a one-handed application of RoboGlove was also utilized for this task.

Fig. 9. Door glass manipulation (illustration only)

For this application, RoboGlove was programmed to close four fingers when commanded by fingertip sensor input. Similar to the crimping application, the control program reduced motor current after the fingers were fully closed based on actuator velocity. In this case, however, the grasp was maintained for a long duration. The glove held the user's fingers closed on the glass until it was commanded to release based on input from a sensor in the thumb tip. It was concluded that RoboGlove technology indeed has potential for reducing the grasping effort required to hold the weight of the door glass during installation into the door.

C. *Space Suit Application*

While extensive testing of the space suit glove is ongoing, component level tests show that the concept has merit. The pressure differential experienced by the glove creates a static offset in the FSR readings, but sufficient range exists in the circuit such that operator intent is clearly distinguishable from the baseline. Test results may show the need for an initialization process to establish this baseline for each session. The team is also experimenting with conduit routing by combining test subject feedback with paths calculated by cable routing features in PTC's Creo CAD software to ensure the conduit placement minimally impacts the operator's wrist range of motion.

VIII. CONCLUSIONS/FUTURE DEVELOPMENT

The GM/NASA RoboGlove is an exciting extension of the mechatronic design philosophy that started with the Robonaut 2 (R2) system. Technology inherited from R2 is well suited for application as an assistive device, which will help users in a range of fatiguing and ergonomically difficult tasks. Its versatility and control flexibility have enabled trials that are providing a wealth of knowledge for future refinements.

Continuing design and research are in progress to improve the functionality and usability of RoboGlove. Future prospects include partnering with medical institutions to assist patients with hand and finger injuries. Work is in progress to integrate the technology with an astronaut's space suit glove and evaluate its effectiveness via ground testing. Additional sensing systems are being explored to fine tune the control algorithms. Refinements to the soft goods design will ease donning and doffing, along with improving dexterity. Finally, more compact actuators and electronics will aid packaging and reduce weight even further.

ACKNOWLEDGMENT

This work represents the effort of a community of researchers at both GM and NASA, and the authors would like to thank them for their technical excellence which produced the RoboGlove. Funding for the current work to integrate RoboGlove technology into a Phase VI space suit glove is provided by the High Performance EVA Glove project.

REFERENCES

[1] Linn, et. al, US Patent 8,511,964, Humanoid Robot.

[2] Diftler, M.A., et al. "Robonaut 2- The First Humanoid Robot in Space" *Proceedings of the IEEE International Conference on Robotics and Automation,* Shanghai China. pp 2178 - 2183, 2011.

[3] Ihrke, US patent 8,467,903 Tendon Actuation System.

[4] Bridgwater, L.B., et al "The Robonaut 2 Hand – Designed To Do Work With Tools". *Proceedings of the IEEE International Conference of Robotics and Automation,* St. Paul Minnesota ,pp. 3425-3430, 2012.

[5] CyberTouch, CyberGrasp, http://cyberglovesystems.com/

[6] Kazerooni, H., et al "The Magic Glove". *Proceedings of the IEEE International Conference on Robotics and Automation*, New Orleans, LA. pp.757 – 763, 2004.

[7] Sasaki, D. Noritsugu, T. Takaiwa, M. and Yamamoto, H., "Wearable Power Assist Device for Hand Grasping Using Pneumatic Artificial Rubber Muscle". Proceedings of the 2004 IEEE International Workshop on Robot and Human Interactive Communication Kurashiki, Okayama Japan, pp. 655 – 660, 2004.

[8] Connelly, L. et. al., "A Pneumatic Glove and Immersive Virtual Reality Environment for Hand Rehabilitative Training After Stroke", IEEE Transactions on Neural Systems and Rehabilitation Engineering, Vol. 18, No. 5, October 2010. pp. 551-559.

[9] Toya, K., Miyagawa, T. and Kubota, Y., "Power-Assist Glove Operated by Predicting the Grasping Mode". Journal of System Design and Dynamics, Vol 5, No 1, 2011, pp. 94-108.

[10] Nilsson, M. et. al., : The Soft Extra Muscle System for Improving the Grasping Capability in Neurological Rehabilitation." *Proceedings of the IEEE/EMBS International Conference on Biomedical Engineering and Sciences, Langkawi*, Malaysia, pp 412-417. 2012.

[11] Martinez, et. al., "A Power-assisted Exoskeleton Optimized for Pinching and Grasping Motions". Proceedings of the 2010 IEEE 36th Annual Northeast Bioengineering Conference, NYC, NY, 2010.

[12] Sorenson, E., Sanner, R., Howard, R., Akin, D. et al., "Development of a Power-Assisted Space Suit Glove Joint," SAE Technical Paper 972323, 1997, doi:10.4271/972323.

[13] Martin, T., et al "Tactile Gloves for Autonomous Grasping with the NASA/ DARPA Robonaut". *Proceedings of the IEEE International Conference on Robotics and Automation,* New Orleans, LA. pp.1713 – 1718 Vol.2 2004

[14] Doherty, M. T., Tufts, D. B., Jacobs, S. E. and Macleod, S. R., "Extravehicular Activity Space Glove Development for Future Space Exploration", Proceedings of the 43rd International Conference on Environmental System, Vail, Colorado, July, 2013.