Active Haptic Control for a Biologically Inspired Gripper in Reconfigurable Assembly Systems

Testing Active Haptic Control through Force Feedback

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Abstract: Haptic feedback for flexible grippers enhances control over human-machine interaction and object manipulation. Force feedback control through a haptic sensory system enables gripping sensitivity for the grasping of fragile components. The development of intelligent gripping systems has the potential to be implemented in Reconfigurable Assembly Systems, (RAS), for on-demand production lines. Advancements in object control and successful object handling for assembling systems were investigated. An active haptic control system was developed to assess the adaptability of gripper appendage grip force through a dynamic pick and place movement. The aim was to determine the force output from a self-adjusting grasping procedure using a haptic feedback control sensory system. The force output data was empirically collected and plotted on a signal verse time graph. The voltage signal representing the actual grasp force throughout a gripping procedure. The testing was performed on a previously manufactured gripper based on a biologically inspired phenomenon called the Fin Ray Effect®. Conclusions and recommendations were made in relation to effective grip force control.

1 INTRODUCTION

Modern assembly systems require superior production rate capabilities. Reconfigurable Manufacturing Systems, (RMS), satisfies the requirements for flexibility and reconfigurability in manufacturing. Production lines are required to be efficient in terms of precise part control and placement (Bouchard, 2014). Reconfigurable Assembly Systems, (RAS) are defined by (Koren and Shpitalni, 2010) as follows: “Reconfigurable assembly systems are those that can rapidly change their capacity (quantities assembled) and functionality (product type, within a product family) to adapt to market demand”.

Flexible fixtures in RAS cater for product variety and changes in part size through adjustable mechanisms in dynamic response environments for on-demand production (Padayachee and Bright, 2013). Flexible grippers are therefore applicable in RAS. The end-effector of a robotic manipulator is essential for part handling (Reddy and Suresh, 2013). Flexible grippers are developed for multi-function and high flexibility in gasping operations for pick and place procedures and fixturing applications.

Grippers are improved through the means of flexibility and performance. Flexibility and performance have an inverse relationship with a one-another shown in Figure 1. Gripper systems with high flexibility sacrifice performance and vice-versa. Grippers possessing adaption to part variety require haptic feedback to increase the performance of gripping.

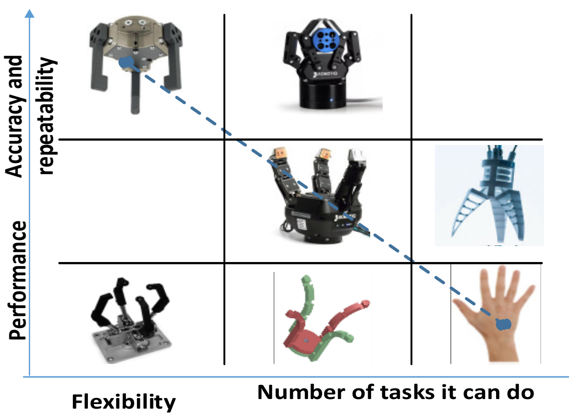

Figure 1: Performance verse flexibility of grippers.

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Product assembly in manufacturing is ineffective in human-computer integration because assembly systems consist mainly of geometric constraints and lack haptic feedback attributes (Xia, 2016). Haptic systems are divided into three (3) focus areas: Human haptics, computer haptics and machine haptics. Human haptics concern the sense of touch between a human and object. The human “intuition” is described as the input to a machine for object manipulation. The algorithms and software utilized in computational and simulated haptic feedback to describe the properties of the interacted object are termed computer haptics.

Machine haptic technology is the focus research of this paper. Machine haptics refers to the haptic touch interfaces between a machine and an object. The development and design of the haptic devices augment and simulate human touch for intelligent gripping systems.

Part handling employing haptic force sensitive systems enable the complete control without human intervention. Surface damage during part grasping is avoided by utilizing minimum force threshold values. Slippages are reduced through force control. Haptic feedback systems allow for enhanced part machine interactions. Haptic feedback systems can be classified as active and passive.

Passive haptic feedback systems are implemented into the monitoring of gipping systems without energy inputs into the actuation of the grippers. Active haptic feedbacks systems possess either partial or full control of force application of gripping device onto the object or computer-generated simulations (Martin, et al., 2013). An active haptic feedback system was investigated and introduced in the design of a force-feedback control system. The active force feedback additionally enables monitoring of force.

Active haptic control is necessary for orientation and input acknowledgement. Haptic systems provide improved mobility for robots in the form of touch sense. Haptic control minimizes human interaction in complex machine mechanisms and movement. Physiological presence is improved through the means of enhancing machines with intelligent control systems using touch.

2 FLEXIBLE GRIPPERS IN LITERATURE

Flexible grippers and fixtures are investigated to substitute dedicated assembly stations that are composed of devoted grasping and fixturing mechanisms. The reduction of time loss per station change in an assembly or disassembly of components decreases overall production time. Modular and/or flexible gripping methods have been recognized to minimize time consumption in assembly station overlay (Molfino, et al., 1999).

A six (6) degree of freedom design of a gripping system for Flexible Fixtureless Assembly, (FFA), was developed by (Yeung and Mills, 2004). The gripper system designed provides functions for both a conventional fixture and reconfigure-able gripper. The gripper is able to change the gripping configurations to suit the assembly procedure and part variety. A drawback to the system was the position of grasp points on the object to be manipulated has to be known. The flexibility in terms of self-adjustment can potentially be compromised.

A reconfigurable gripper design was investigated by (Molfino, et al., 2006), using modular fixture units to assemble and disassemble a washing machine. The gripper mechanism consisted of rigid links and hinges. The modular fixture device incorporates a fuzzy controller to implement force control to identify extrusions on the part surface. An anthropomorphic modular reconfigurable gripper purposed by (Staretu, 2015), using exchangeable finger orientations. The modularity of gripper appendages increases grip variation for size and shape of objects.

A gripping mechanism consisting of Fin Ray Effect® based appendages are described by (Tharayil, et al., 2017). Self-conformity was investigated in the Fin Ray structure and implemented in a self-adjustment gripper system. The Fin Ray Effect® is described by the deformation of a V-shaped rib structure through an applied force P (Pfaff, et al., 2011), illustrated in Figure 2. The undeformed rib structure is shown in A and the deformed rib structure is shown in B.

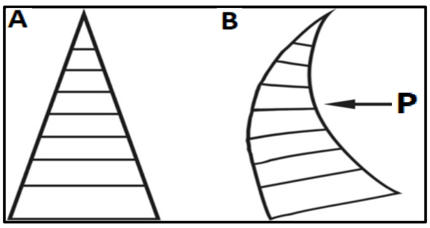

Figure 2: The working principle of the Fish Fin Effect® (Pfaff, et al., 2011).

Potential flexible grippers can be categorised as: multi-fingered grippers, enveloping grippers and malleable grippers. The design criteria comparison is shown in Tables 1, 2 and 3, according to the advantages, disadvantages and significant application.

A design should be suitable for an applicable gripping function.

Table 1: Advantages of flexible grippers.

Design	Advantages
Multi-fingered grippers	Flexibility gripping for different object shapes, gripping wit force feedback
Enveloping grippers	Adaptability to mould around the object
Malleable grippers	Adaptable to different shapes, reliable gripping

Table 2: Drawbacks of flexible grippers.

Design	Drawbacks
Multi-fingered grippers	Control complexity
Enveloping grippers	Low force control capability
Malleable grippers	Low gripping dexterity

Table 3: Significant application of flexible grippers.

Design	Significant Application
Multi-fingered grippers	Grasping all shaped objects with force control
Enveloping grippers	Grasping oddly shaped and unknown objects
Malleable grippers	Grasping unknown and specially deformed objects

3 HAPTIC CONTROL FOR GRIPPERS IN LITERATURE

Haptic feedback is utilized in gripper systems enabling force feedback control. The grasping sensitivity is attained through haptic feedback. Force management reduces the unintended damage of handled part and gripper mechanisms. The force control decreases the probability of unwanted slippage and increases self-adjustability.

A force feedback control system through a miniature load cell for a rigid 3d-printed 2-finger gripper is proposed by (Lipina, et al., 2011). Object manipulation was required in the circumstance of a power failure during the extension of a robot arm. The force of the gripper was influenced through the changing the input current (Ampere) and the force was measured through a miniature load cell.

A haptic control system utilizing Shape Memory Alloys, (SMA) as a gripper actuator, is presented by (Yan, et al., 2012). The haptic control is performed by means of potential difference (Voltage) across micro-deformations from Polyvinylidene Fluoride Films PVDF), due to their piezoelectric properties. The PVDF sensors are embedded as tactile sensors.

A tele-manipulation (master-slave operation) for a gripper system was presented by (Park, et al., 2016) to replace human presence at task site. The telepresence extends human touch to the environment remotely. The haptic sense interface utilizes Force Sensitive Resistors (FSR) and laser distance sensors inserted in the slave device (the gripper). The master device (remote controller) manipulates the force feedback by means of magnetorheological (MR) glove acting as force-control, increasing and decreasing force commands.

4 PREVIOUS DESIGN OF A 4-FINGER GRIPPER

4.1 Mechanical Design of Gripper

The study was conducted on a previously designed Fin Ray Effect® based gripper that was developed by (Basson, et al., 2017). The 4-finger gripper was designed and based on the Fin Ray Effect®, shown in Figure 3. The design was inspired by the FESTO® Multi Choice Gripper (FESTO, 2014). The gripper appendage design was based on conformity studies investigated in the design of the TIHRA gripper (Crooks, et al., 2016).

The design was manufactured from Acrylonitrile Butadiene Styrene, (ABS), plastic and by means of 3D printing. The mechanical properties of ABS allow for flexibility and strength to sustain deformation without failure. The Elastic Modulus (E) of ABS plastic is 2 GPa, the Poisson's Ratio (υ) is 0.4 and the Yield Stress (σ_y) is 45 MPa.

Figure 3: 4-Finger proposed gripper design (Basson, et al., 2017).

4.2 Design and Simulation of the Selected Appendage

The rib design for the appendage was selected from four (4) geometries and was described by (Basson, et al., 2017), shown in Figure 4. Geometry 1 utilized the traditional Fin Ray Effect® concept with parallel ribs. Geometry 2 was designed with a slanted rib structure. Geometry 3 comprised of concentric curved ribs. Geometry 4 possessed the rib structures of Geometry 3 and Geometry having curved and slop structures. A Finite Element Analysis, (FEA), was performed on the various rib structures and the conformity was examined in relation to the Fin Ray Effect®. The design appendages demonstrated self-conformity with respect to rib deflection.

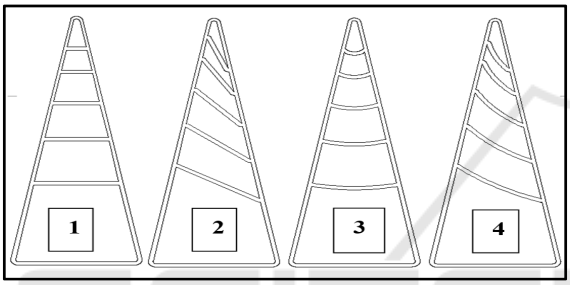

Figure 4: Rib structure design for appendages (Basson, et al., 2017).

A non-linear static analysis was performed and Geometry 4 was found to be the best-suited rib structure, illustrated in Figure 5. A force of 10 N was applied against the gripping face of the appendage. The stress and deflection results from the simulation yielded 19.84 MPa and 2.28 mm respectively. The deflection was 29.3% larger than that of Geometry 1.

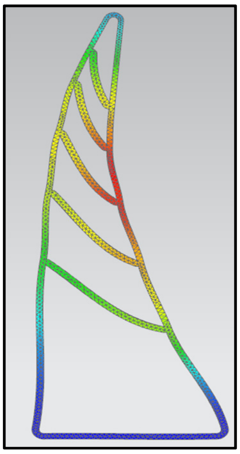

Figure 5: Deflection shape of Geometry 4 (Basson, et al., 2017).

4.3 Gripper and Robotic Arm Integration

The gripper system was installed onto the end-effector attachment of a FANUC M-10iA robotic arm. The gripper system consisted of the actuated gripper and the force feedback sensory system. The actuator employed was a NEMA 17 stepper motor and was connected to stepper motor controller. Force Sensitive Resistors, (FSR), were utilised as haptic feedback for the gripper, shown in Figure 6. The stepper motor controller and the sensors were linked to an Arduino Mega 2560 microcontroller. The gripper system was connected through a wire system to the respective electronic components illustrated in Figure 7.

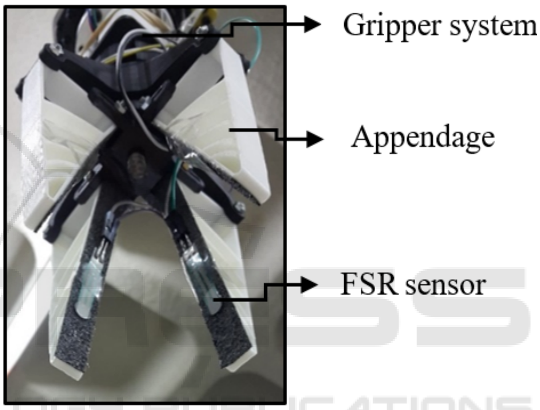

Figure 6: Installed sensory system.

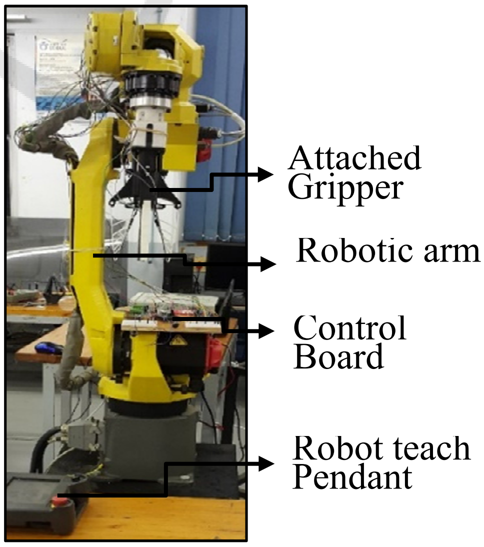

Figure 7: Frontal view of robot gripper and gripper system.

The solution was proposed as an alternative for traditional grippers. Flexibility is increased by selecting and designing appendages to mimic human-like fingers in a grasping motion. The intention of the design was to test and manufacture a lightweight and flexible gripper for the ease of instalment. The haptic system was implemented for operational environments where product structural integrity through handling would not be compromised. The gripper actuation method using motor actuation was changed in comparison to FESTO's MultiChoiceGripper®, which used pneumatic actuation. The rib structure was modified therefore improving grasping properties from the traditional rib design.

5 ACTIVE HAPTIC CONTROL

5.1 Pseudocode and Flow Diagram for the Mechatronic Control

The pseudocode described the procedural layout of the mounted gripper system and included haptic control, shown in Figure 8. The program was initiated and started the operation procedure. The system located the grasping location of the object by means of a written input code. The object was grasped with aid of push-button control, which resembled a written code that initiated the closing of appendages to grasp the object. The system was verified for an accepted grasp. The system reinitiated the grasping procedure when the grasp was unacceptable.

Acceptable grasps resumed enclosing the gripper appendage and exceeded a lower force threshold (A). The lower force threshold initiated automatic closing of the gripper until a high force threshold (B) was attained. The gripper was programmed to open automatically until a force threshold (C) was met. The force threshold (C) value was located at a fraction value below threshold (B). The variation between (B) and (C) existed for self-adjustment just below the force magnitude required to damage the grasped object. The grip intensity self-regulated when unintended grip force interferes were present in the required force grip when experiencing dynamic motion.

The program identified the release location. A push button or over-riding code was programmed to disengage self-regulating loop for the release of the object. The program ended and started a new operation cycle.

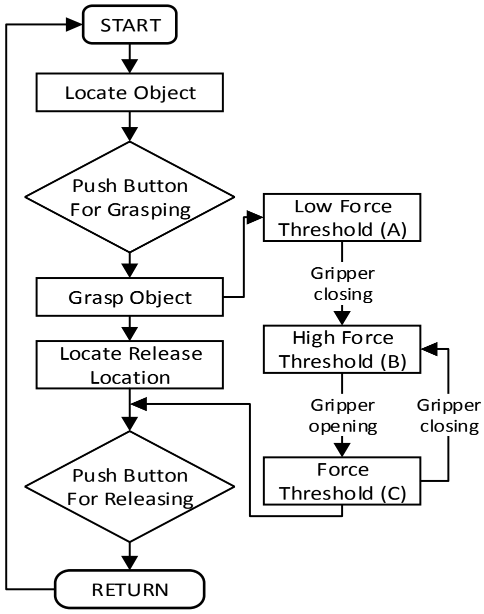

Figure 8: Operational pseudocode for the gripping system.

The mechatronic system architecture of the gripper system consisted of a software architecture and a mechanical architecture, shown in Figure 9. The gripping sequence was initiated by means of push-button input through human involvement. The haptic input signal from the FSR sensors was converted and relayed to the system controller. The system controller transmitted the signal to the stepper motor controller and manipulated the stepper motor. The manipulation of the actuation influenced the grip movement direction on the gripper.

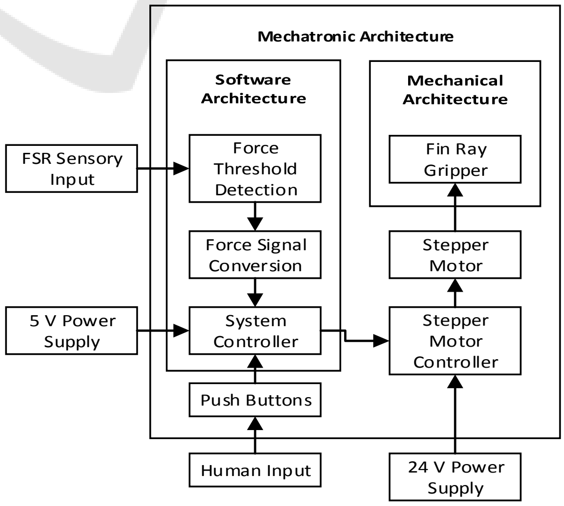

Figure 9: Logic flow diagram of haptic gripper system architecture.

5.2 Force Feedback Control Loop

The force feedback control loop is illustrated for the haptic control of the gripper system. Initial force input is recorded through a push-button resembling an input voltage. The threshold values are the required values for the control system to regulate between the opening and closing the gripper fingers around the object. A constant input voltage signal was supplied through the micro-controller and motor-controller, by means of an external power source. The signal required was transmitted to the actuator in the Fin Ray gripper. The signal value was retrieved from an FSR and relayed to be compared to the input signal. The force output was corrected with the condition that the output signal value was incorrect in comparison with the input signal value. The corrected voltage value was applied to the directional motion of the actuator. The haptic control layout is shown in Figure 10.

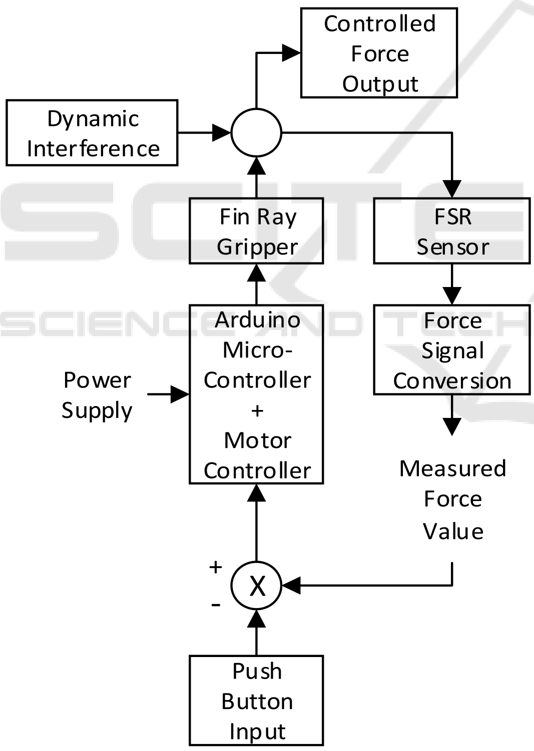

Figure 10: Force feedback control loop.

The interference forces were produced from the robot arm's rotational and translational movement. The object experiences force components which were described by inertia forces *a,* centripetal forces *b*, gravitational forces *g* and Coriolis forces *c* (Yang, et al., 2016). The force vector was described by the Lagrangian formula in Equation 1.

$$a(\boldsymbol{q})[\ddot{\boldsymbol{q}}] + b(\boldsymbol{q})[\dot{\boldsymbol{q}}\boldsymbol{q}] + c(\boldsymbol{q})[\ddot{\boldsymbol{q}}] + g(\boldsymbol{q}) = \tau \quad (1)$$

Where:

$\boldsymbol{q}$: Vector of joint angles.

$a(\boldsymbol{q})$: Symmetric, bounded, positive definite inertia matrix.

$c(\boldsymbol{q})$: Coriolis forces.

$b(\boldsymbol{q})$: Centripetal forces.

$g(\boldsymbol{q})$: Gravitational force

τ: Vector of actuator torques.

Object manipulation required control of the force input magnitudes of the maximum grip. A control system was conceptualized utilizing a gripper based on the Fin Ray Effect®. The system integration worked collectively to coincide with self-adjustment requirements.

6 TESTING OF ACTIVE HAPTIC CONTROL

6.1 Previous Static Testing Overview

A static mass holding test was performed on the gripper system. The 3-finger and 4-finger gripper configuration were tested according to gripping repeatability. An object was grasped and the mass was gradually increased until a maximum load of 2435 g was reached. Geometry 4 proved to be the most effective. The system was 97.3% repeatable in grasping the maximum object mass. The experiment was repeated fifteen (15) times for each configuration and rib structure to maintain empirical accuracy (Basson, et al., 2017).

A dynamic and static qualitative gripping test was performed on the gripper system. The 4-finger and 3-finger gripper system was evaluated by gripping various objects to determine effective conformity in gripping various shapes, shown in Figure 11. The following shapes were gripped: A sphere (A), a cube (B), a triangular prism (C), cylindrical extrusion screw (D) and a crazy cube with various shaped sides (E). The 4-finger gripper performed the most satisfactory with no slippages occurring, and the 3-finger gripper slipping when handling 4-sided prisms. The experiment was repeated five (5) times for each configuration and rib structure to maintain empirical accuracy (Basson, et al., 2017).

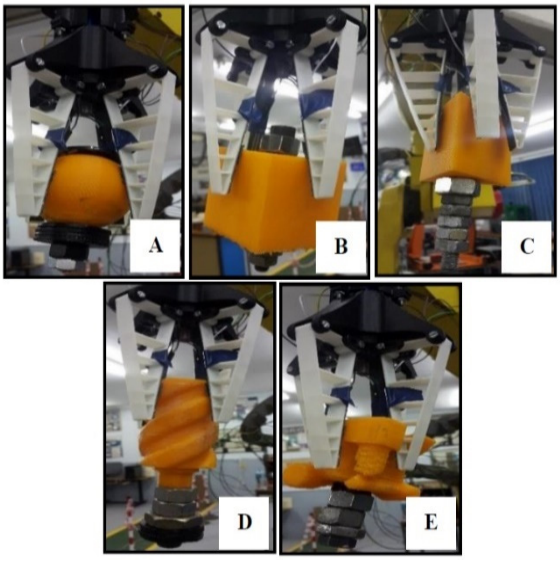

Figure 11: Dynamic test for 4-finger gripper holding a concentric sphere shape: A) Geometry 1, B) Geometry 2, C) Geometry 3, and D) Geometry 4.

6.2 Dynamic Testing Preparation

A path plan program is described for the robotic arm input. The path plan is visually described in Figure 12. The path plan describes a dynamic motion that the end-effector follows in simulating a pick and place procedure. The dynamic motion simulates a controlled experimental environment and the experiment was repeated multiple times for the same motion.

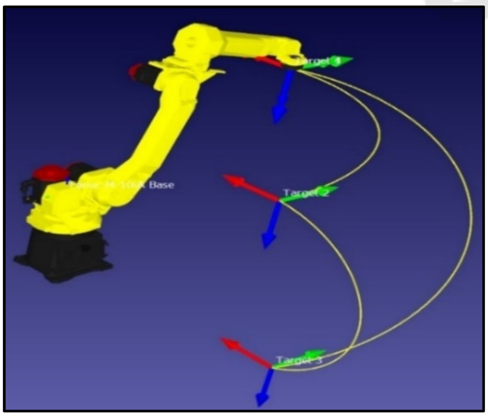

Figure 12: Graphical representation of the robotic arm path plan.

Signal feedback values were received from the FSR sensors. The voltage and mass loading on the sensor experienced a non-linear relationship, due to the shearing of the sensor material, illustrated in Figure 13. The calibration was conducted for all four (4) sensors. The voltage output values varied from one sensor to the other, as a result of the sensitivity in shear mechanics and material thickness that varied in each sensor.

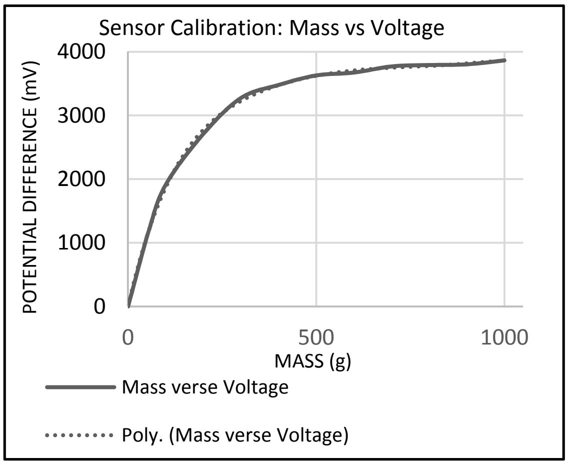

Figure 13: Mass verse voltage calibration.

The output value program was calibrated accordingly to produce a potential value in millivolts. The following Equation 2 was used to calibrate the output values:

$$V\_out = (val * V\_in)/1024 * 1000 \qquad (2)$$

Where:

V_out: Output voltage (mV)

val: Value reading output (-)

V_in: Input voltage (5 V)

The relative error for the sensors has been calculated for 45 readings representing 4.5 seconds using Equation 3. The object was grasped constantly to determine the average relative error for the Force Sensitive Resistors incorporated into the haptic feedback system for the gripper, shown in Figure 14. The average relative error was determined for the mass loading for each sensor and the expected sensor performance is shown in Table 4.

$$err = 100 \times (Val_{act} - Val_{exp})/Val_{exp} \qquad (3)$$

Where:

err: Relative error

Val_{act}: Value reading

Val_{exp}: Expected reading

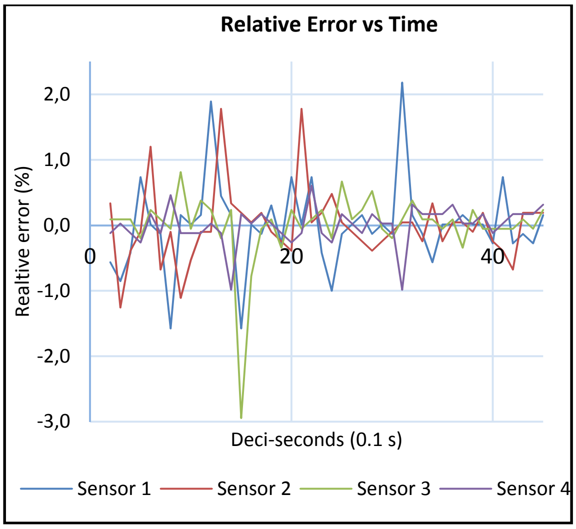

Figure 14: Relative error verse time for FSR sensor 1, 2, 3 and 4.

Table 4: Average relative error for sensor values.

	Expected mass value (g)	Expected Voltage (mV)e	Average relative error (%)
Sensor 1	552.25	3378	-0.0003
Sensor 2	429.02	3534	-0.0043
Sensor 3	483.01	3527	-0.0020
Sensor 4	296.08	3173	0.0027

6.3 Dynamic Testing without Feedback Control

Dynamic testing was performed to determine the force throughout a dynamic movement without a feedback control at a low robot speed of 250 mm/s. The spherical specimen was used as the test piece to maintain conformity and simultaneous contact of all four (4) sensors. The object was gripped and cycled through the movement described in Section 6.2. The intended movement was described in three (3) time lapses: A ten (10) second pause, a ten (10) second dynamic motion and a ten (10) second pause. The experiment was repeated five (5) times for each configuration and rib structure to maintain empirical accuracy.

The data values retrieved to illustrate self-conformity of the Fin-Ray Effect® while grasping through dynamic motion. Increased voltage variations display the external force interference due to the dynamic force components described in Section 3.3. The voltage verse time graph, illustrated in Figure 15, depicted increased voltage values during and following the dynamic motion.

An average grip force in grams was calculated to determine a minimum holding strength. The mass of the specimen was 320 g and the average holding force required was 1146 g (286.5 g per appendage).

A disadvantage from the self-conformity characteristics and high loading variations due to force interferences is that fragile and brittle components i.e. lightbulbs have the potential to fail under varying force and shock loadings. A dynamic experiment for active haptic feedback control is required to control the force variation. The control response is of importance as force changes occur very rapidly.

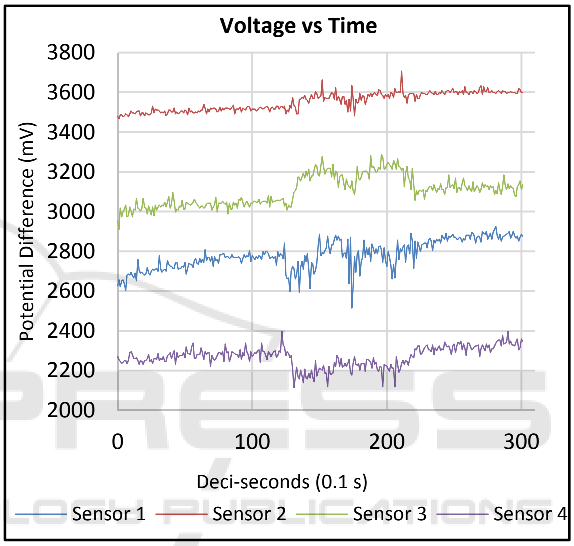

Figure 15: Voltage verse time for 4-finger gripper: Geometry 4 with 250 mm/s speed.

6.4 Dynamic Testing of Active Haptic Feedback Control

Dynamic testing was performed to determine the force throughout a dynamic movement utilizing an active haptic control at a high robot speed of 2000 mm/s. The spherical specimen was used as the test piece to maintain conformity and simultaneous contact od fall four (4) sensors. Identical path planning, estimated time lapses and test runs were employed that were used in the experiment.

The data values illustrated force control for high-speed applications, shown in Figure 16. The force interference was minimized and force increased, due to self-conformity, was reduced. High signal spikes were still present as result of noise from the environment, voltage imbalances from ineffective material shearing and impaired actuation response.

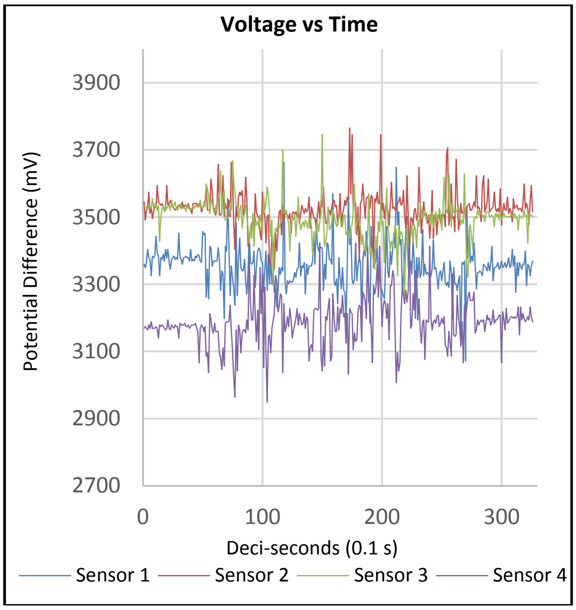

Figure 16: Voltage verse time for 4-finger gripper: Geometry 4 with 2000 mm/s speed.

The threshold values for the force control are as follows: Low threshold value (A) was at 977 mV, the high threshold value (B) was at 3418 (mV) and the threshold value (C) was at 3345 (mV). The high value indicated the critical damage value for fragile objects. The input signal for value (B) is influenced according to the type of delicate objects that are gripped. The experiment was repeated five (5) times. Results illustrated actuation response to force input values to sensors. Signal values overcoming threshold values were countered through the opening of the gripper fingers to reduce high force loading on contact surfaces.

7 CONCLUSIONS

The paper analysed a haptic feedback control for a biologically inspired gripper. The gripper was designed and developed based on the Fin Ray Effect®. The study reviewed conformity characteristic regarding stress and deflection performed through an FEA simulation. A haptic feedback control flow diagram describes the force regulation through actuation of the gripper. Repeatability of the gripper was determined through static testing that was performed in previous studies. The gripper was tested to verify conformity for grasping of different shapes in prior investigations. The 4-finger gripper utilizing Geometry 4 was established to be the preferred combination.

A dynamic test was performed on the gripper utilizing force feedback with and without active haptic control. Testing without active feedback was performed in prior studies and illustrated force variation and self-conformity due to dynamic interferences. High force impulses can potentially damage fragile components and as a result, an active haptic feedback control system was required. The system was tested at lower operational speeds to emphasise that force fluctuations have involved that exhibit the potential to damage handled components.

The system was tested employing an active haptic feedback control and high operational speeds were exercised in the experiment. The results showed the force before and after the dynamic motion was stabilized, but high force impulses were visible during the movement due to force interferences.

A dynamic test was performed on the gripper utilizing force feedback with and without active haptic control. Testing without active feedback was performed in prior studies and illustrated force variation and self-conformity due to dynamic interferences. High force impulses can potentially damage fragile components and as a result, an active haptic feedback control system was required. The system was tested at lower operational speeds to emphasise that force fluctuations have involved that exhibit the potential to damage handled components.

The system requires a faster response to force variation. Force impulses can be minimized by increased motor speed for opening and closing and reducing signal noise. The type of sensor used also affect the sensitivity of the results and higher ranged force sensors should be used with higher accuracies.

The biologically inspired gripper system with active haptic control has the potential to be implemented in production application where handling of fragile objects is performed. Typical objects that could be gripped and manipulated in this investigation are glass components i.e. light bulbs, fragile foods i.e. eggs, etc.

Haptic feedback control possesses drawbacks pertaining to environment interaction. Actuator response to environment requires to be rapid when an impact occurs. High force impact loading was observed and as a result affects the control of the gripper system negatively.

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