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DEVELOPMENT OF HEXAQUAD ROBOT: MODELING AND FRAMEWORK

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ABSTRACT

This paper presents a proposed reconfigurable multi-legged robot named Hexapod-to-Quadruped (Hexaquad) robot. Reconfigurable legged robot is one of the robotics research areas that is generally focused on optimizing the usage of leg during locomotion. Until recent years, most of the researches emphasized on leg reconfigurable design in order to solve the fault tolerant, stability, multi-tasking and energy efficiency. However, the emphasis of the Hexaquad robot is on providing optimum leg usage, actuation configuration as well as satisfying the legged robot stability criterion in reconfiguration mechanism. Inspired from several living creatures, such as insects, crustacean and peristaltic creatures, Hexaquad is designed and modeled to perform flexible spine for leg adjustment and foot-to-gripper transformation. The design also implements the indirect and parallel actuation configuration on leg-joint motion for optimum torque on the joint of each leg without motor/actuator mass affect that commonly happens in multi-limbed system with direct drive configuration. The minimum torque on each joint of the leg is calculated using the static torque calculation on multi-link structure before the actuator/motor is selected, and verification is done by performing fundamental testing on the leg's movement and standing using direct switching and supply voltage. Further testing and analysis were conducted on the gripper by performing gripping tests using materials of different weight and shape versus total load current on the leg's actuators. Stress and displacement testing and analysis were also done on the foot-to-gripper (FTG) structure of Hexaquad robot. The results show that the FTG is able to hold 50N forces without any breaking point being detected as well as able to maintain its shape, strength and position upon receiving the forces (surpassing the main objective to lift a 5kg load).

Keywords: hybrid bio-inspired robot, reconfigurable mechanism, foot-to-gripper transformation.

INTRODUCTION

A bio-inspired or biomimetic system design and control engineering has become a favorite area in recent robotic research and development. Legged robot, or so called active suspension vehicle (ASV),is one of the bio-inspired system that mimicked horse biological structures was started in1960s[1].With significant advantages compared to the wheel type robot/vehicle, a legged robot is capable of navigating irregular and mountainous terrain. In actual situation, earth's landmass is accessible to existing wheeled and tracked vehicles, but a much larger portion can only be reached by animals on foot[2]. Moreover, animal on foot is able to climb and walk on the bottom surface of water. Consequently, several studies and development have been done in the area of legged robot by previous researchers to achieve good adaptability, function, high flexibility and extensibility with extreme and unknown terrain. Until recently, most of the progresses are in system mechanism, structure design/configuration, and workspace on giving efficient design and reducing control complexity in a legged and multi-legged robot. However, some studies have been carried out in designing a reconfigurable legged robot, in which the effectiveness and optimization of the leg usage were considered. Energy efficiency was one of the reasons for the studies, other than fault tolerant [3], multi-tasking

[4] and stability [5] in designing a configurable multi-legged robot. Meanwhile, optimization of the actuators used on the robot's leg with the emphasis on designing better under-actuated or parallel actuation leg configuration, such as reported and implemented in [6, 7], has also become another focus area. However, this is in contrast with the effort of reducing the complexity in robot control architectures such as reported in [8], in which additional converter module is needed.

However, some researchers took up the challenge and contributed ideas using intelligent system and robust control approaches. For example, the closed-form solution was introduced by Agheli *et al.* to derive the closed-form equations of the boundary of the constant-orientation workspace used by axially symmetric hexapod robots. The proposed approach can be applied in a robot system with non-symmetric and non-identical kinematic chains [9]. Moreover hormone-based distributed control has been proposed and implemented on CONRO robot gait reconfiguration between caterpillar and spider gait mode [10].In addition, the organic self-configurable was proposed in hexapod robot named OSCAR from University Lübeck, with the emphasis on overcoming the malfunction leg(s) and optimizing the overall energy during locomotion by performing self-amputation [11].

This study has taken the initiative and the challenge by proposing a reconfigurable multi-legged robot with bio-inspired configuration, named Hexapod-to-Quadruped (Hexaquad) robot (Patent Applied)[12]. Hexapod is astatically stable multi-legged robot configuration, while quadruped is a dynamically stable configuration of multi-legged robot with reference to the principle of leg stability [13]. In principle, a multi-legged robot with more than four legs has the potential to be reconfigured into one with less than four legs, such as a quadruped and bipedal configuration (critical configuration)[5].This paper starts with the discussion on the conceptual design and modeling of Hexaquad robot. This is followed by the modification on Hexaquad mechanism and model from the viewpoint of the actual framework. Finally is the explanation on the fundamental testing and analysis with the emphasis on Hexaquad leg and gripper fundamental movements, followed by a brief discussion on foot-to-gripper testing and analysis.

HEXAQUAD CONCEPTUAL DESIGN AND MODELING BASED ON HYBRID BIOLOGICAL CREATURES

The proposed configurable Hexaquad robot is inspired from a hybrid of biological anatomy of selected living creatures, which include insects, crustacean and peristaltic organism, as shown in Figure-1. As one of the multi-purpose active suspension vehicle (ASV), Hexaquad robot is expected not only to be able to walk on irregular and mountainous terrain, but also able to perform other tasks such as picking and placing obstacles as well as climbing.
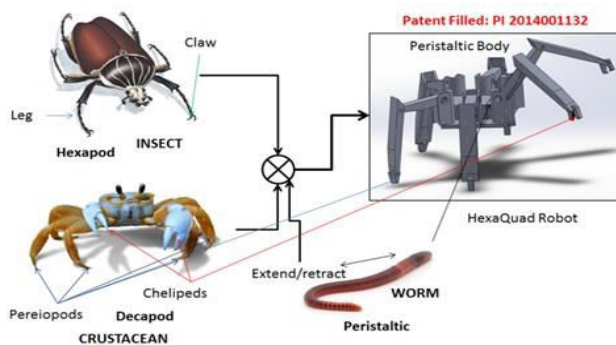
**Figure-1.** Proposed Hexaquad robot with hybrid bio-inspired configuration

The prismatic spine of the proposed Hexaquad robot is inspired by the peristaltic movement of a worm as shown in Figure-2, while the 3 degree-of-freedom (DoF) foot-to-gripper (FTG) leg configuration is inspired by the movement of a crab as shown in Figure-3. The two flexible and movable legs on the prismatic spine allows the Hexapod robot to identify its center of gravity (CoG) and center of pressure (CoP) to realize the Hexa-Quad transformation [5]. Moreover the arthropod configuration in a crustacean is considered as hybrid of hexapod and decapod creatures as the configuration has the ability to optimize a leg as an arm in a particular situation. In order

to optimize the use of actuators and energy, Hexaquad robot is modeled with the same capability as an arthropod creature, as shown in Figure-2[12]. Moreover, the foot is fully utilized in hexapod mode as shown in Figure-2(a) compared to that in quadruped mode as shown in Figure 2(b), in which FTG is performed in the latter mode.
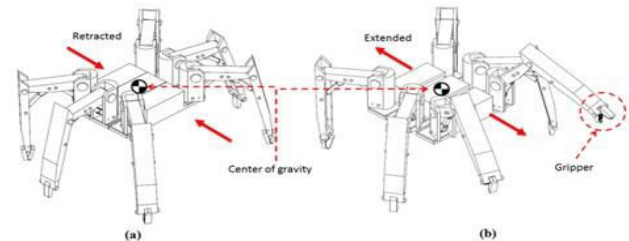
Figure-2. Perspective view of Hexa-quad transformation implemented in Hexaquad robot: (a) Hexapod mode (b) Quadruped mode.

As shown in Figure-3, linear actuators are used to move the merus and carpusto perform parallel actuation or muscle-based mechanism; this actuation will result in higher torque on the joints compared to that using direct actuation with rotary motor. In hexapod mode, the tip of the foot closes, thus enabling the leg to perform crawling or walking function.
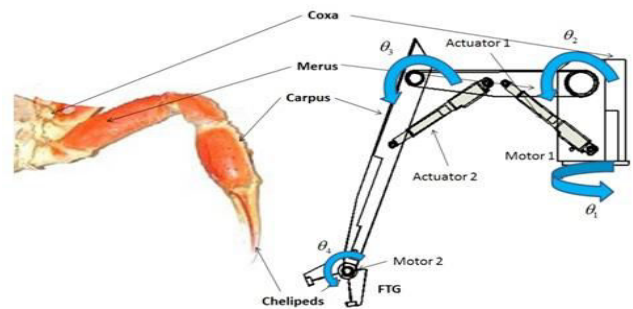

Figure-3. Hexa-quad robot leg's configuration with indirect/parallel actuation inspired from crab's leg.

HEXAQUAD ACTUAL MODEL WITH MECHANISM MODIFICATION

The proposed bio-inspired Hexaquad robot has been remodeled for fabrication purposes by considering the following aspects: type of material to be used for the frame, load/payload torque selection for the motor/actuator, and water resistance (anti-corrosion) since the robot will be deployed for underwater operation. The fabrication is focused on three main designs, which are leg design, prismatic body design and foot-to-gripper design. For the frame of the robot, aluminum alloy 6061 was selected as the main material to be used in the fabrication. Other than being anti-corrosion, its properties meet the requirements for the Hexaquad robot as shown in Table-1.The concept used in remodeling the Hexaquad robot is called Actuating Frames, in which the actuators/motors used are a part of the body frame, hence reducing major frame fabrication. As depicted in Figure-4, three types of motors/actuators have been selected for the remodeled

Hexaquad robot, which are linear actuator, tubular actuator and bipolar stepper motor. As illustrated in Figure-5, tubular actuator is used as Link 2, linear motor with spur gear as parallel actuator for Link 1, and bipolar stepper motor as shoulder motor. The overall dimension of the fabricated Hexaquad model is shown in Figure-6.
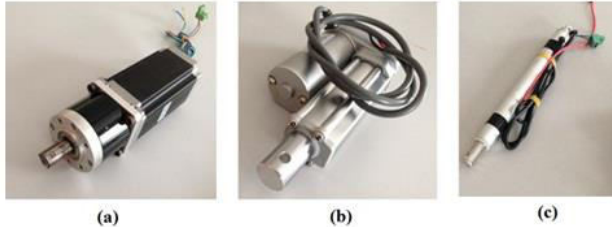

Figure-4. Type of motor and actuators used in Hexaquad robot structure: (a) Bipolar stepper motor, (b) Linear actuator (DC type), (c) Tubular actuator (DC type).
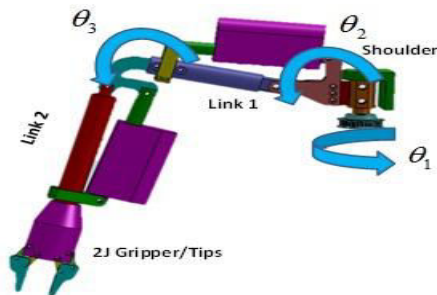

Figure-5. Model of Hexaquad leg (fabrication model).

The prismatic mechanism is realized using a linear track that is driven by a bipolar stepper motor as shown in Figure-7. The difference between the conceptual model and the actual/modified model is in the movement of legs. In the conceptual model as shown in Figure-7(a), the two outer legs attached to the holder are movable; whereas the middle leg is movable in the actual model as shown in Figure-7(b).The modification was made after considering the center of gravity of the robot; the robot would be more stable during transformation mode if the center leg is movable rather than the two end legs, and consequently reducing the complexity of stability control.
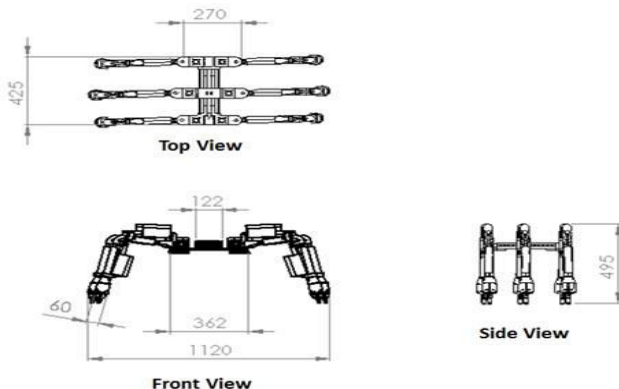

Figure-6. Hexaquad overall isometric view (dimension in mm).
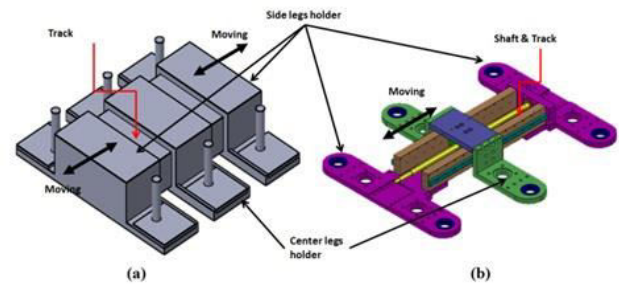
Figure-7. Hexaquad body and spine configuration: (a)Conceptual model, (b) Actual model.

On the other hand, in the actual model, FTG is applied to all legs as shown in Figure-8, instead of the design used in the conceptual model shown in Figure-2. This decision was made in order to prepare for the possible future operations, which include climbing, and wall holding. Figure-8 shows the real Hexaquad robot that has been fabricated, and the specification of the mechanical and driven components is as tabulated in Table-2.
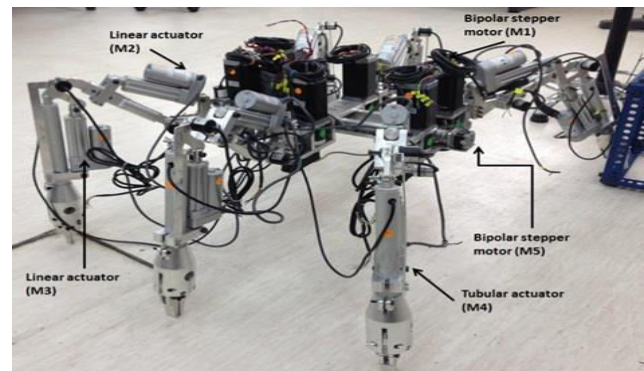
Figure-8. Actual Hexaquad robot system.

Table-1. Specifications of the Hexaquad robotic system.

Item	Value	Remarks
Length [m]	0.9	-
Width [m]	0.42	-
Height [m]	0.43	-
Total Weight [kg]	50kg	-
Linear actuator Load [N], Voltage Input [V] Current [Amp]	200, 12, 2	6 Unit
Tubular actuator Load [N], Voltage Input [V] Current [Amp]	12, 200, 12	12 Unit
Bipolar Stepper, Torque [N/m], Voltage Input [V] Current [Amp]	54, 4.5, 3	6 Unit
Bipolar Stepper Motor (Body) Torque [N/m], Voltage Input [V] Current [Amp]	3, 5.4, 0.8	1 Unit

MINIMUM TORQUE CALCULATION OF EACH LEG'S JOINT FOR MOTOR/ACTUATOR SELECTION

To determine the minimum torque required on each joint on the robot's leg, several calculation has been

done that considered the targeted payload W_p. It is crucial to determine the torque about θ_1 or torque on shoulder τ_s in legged robot design since the highest torque/force will be on the shoulder since it has to supports the body and carry the load. Referring to Figure-9, the torque is calculated as follows, where

$W_B =$ Weight of robot's body

$W_L =$ Weight of target load

$W_n =$ Weight of robot's leg

Then;

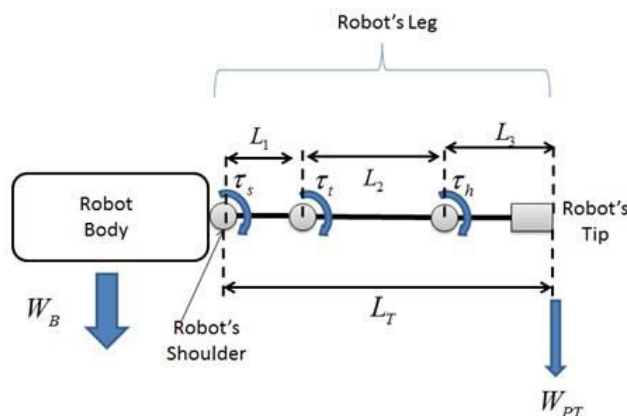Total payload (W_{PT}) can be expressed as in Equation1:

$$W_{PT} = W_P + NW_n \qquad (1)$$

where N is the minimum number of legs on the ground during walking and W_p is the payload of robot's body that can be calculated as in Equation2:

$$W_P = W_B + W_L \qquad (2)$$

Thus, the minimum torque about θ_1 can be expressed as in Equation3:

$$\tau_s = \frac{W_{PT}(g)}{N} L_T \qquad (3)$$

Figure-9. Torque and weight vector for one leg of Hexaquad robot.

where g is the standard value of the earth's gravity, while L_T is the maximum length of the leg, where $L_T = L_1 + L_2 + L_3 \approx L_2 + L_3$ since $L_1 << \{L_2, L_3\}$ as shown in Figure-9. The minimum torque about other joints can be expressed as in Equation 4 and Euation 5. Table-3 shows the actual value for each parameters and minimum torque required for each attached actuators to one leg of Hexaquad robot. For the Hexaquad system, the total weight of the robot is about 40kg and the minimum number of leg while standing on the ground (during quadruped mode) is 2 legs.

$$\tau_t = \frac{W_{PT} g}{N} (L_2 + L_3) \cong \tau_s \qquad (4)$$

$$\tau_h = \frac{W_{PT} g L_3}{N} \qquad (5)$$

From the torque of each motor/actuator capacity as shown in Table-2, it can be concluded that the maximum payload that can be carried by Hexaquad robot is $15kg \le W_p \le 20kg$ with reference to the Equation 6 (extracted from Equation 3):

$$W_p = \frac{N\tau_s}{gL_T} - NW_n \qquad (6)$$

Table-2. Hexaquad parameter values obtained from the minimum torque calculation.

Parameter	Value
W_n	4kg
W_B	5kg
W_L	5kg
W_{PT}	18kg
L_1	20cm
L_3	40.5cm
L_T	70 cm
$\tau_s \approx \tau_t$	6.3Nm
τ_h	3.645Nm

FOOT-TO-GRIPPER MECHANICAL DESIGN AND MODEL FOR FABRICATION

A special feature of the Hexaquad robot is that its foot is optimized as a gripper, which is inspired by crab's chelipeds. In actual situation, implementing direct drive on a joint is very difficult as high torque is needed to hold the gripper when the robot is in foot mode. The high torque would require a big rotary motor as the torque is proportional to the gear ratio or high current winding to produce large horse power. Therefore, scissoring concept is applied for the FTG actuation, as shown in Figure-10, which produces high torque using optimum-sized linear type actuator. The linear movement of the shaft will cause the tips to come together (foot) or split (gripper) as shown in Figure-10(a) and (b), respectively. Tubular actuator, an indirect drive DC motor that is available in high torque capacity, is used in the actual Hexaquad robot as part of the leg frame (Link 2) as shown in Figure-5 as well as a puller shaft to split the tips as shown in Figure-10(b).
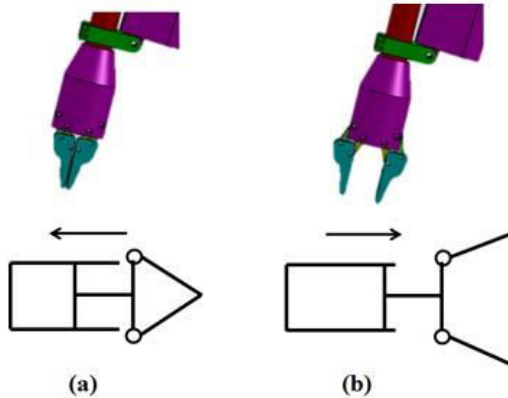
Figure-10. Hexaquad FTG configuration; (a)Foot/Tips mode, (b) Gripper mode

EXPERIMENTAL AND BASIC TESTING ON HEXAQUAD ROBOT SYSTEM

As common practice in development process, the basic testing is done in order to analyze and test its fundamental operation. Two tests has been conducted on the Hexaquad robot: the fundamental leg movement using direct switching and DC power supply, and FTG gripping test with stress and displacement. In the leg movement test, the movement is started using a manual controller directly connected to the power supply and switching is developed in order to control the poles of each actuator attached to the Hexaquad's leg as shown in Figure-11.The test is conducted on a desk by moving each leg in parallel or synchronous as shown in Figure-12. The test showed that the attached actuator is able to move the frame of the leg as expected with optimal dragged current around 3 to 8 Amps per leg. The tests is further conducted with SLD[5] transformation-liked movement, during which the two front legs are set to be hanging or released, while all other legs is positioned in a stable standing quadruped mode as shown in Figure-13. This test verified that the holding torque for each actuator is sufficient and reliable to statically standing this robot either in hexapod mode as shown in Figure-13(a) or quadruped mode as shown in Figure -13(c).

The FTG gripping test is done by conducting several experiments and analysis, which include stress and displacement analysis using actual solid model of Hexaquad robot. The analyses were conducted in order to verify the force exerted by FTG at certain load. FTG testing and analysis is divided into stress and displacement formation analysis (software), and grasping on different-shaped loads with various weight (hardware).
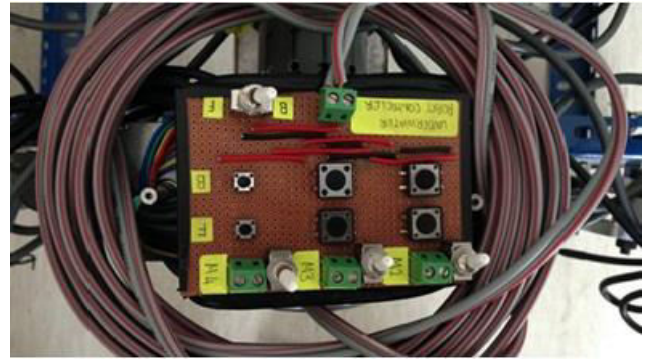
Figure-11. Manual controller for actuator moving test.

The focus of the gripping test is on the force and torque of the gripper using a variation of loads. The ability of the gripper to grasp and hold on to its load dependson the friction encompassed in its jaws. The friction is totally dependent on the gripping process and how the surrounding jaws are cradling the grasping part/load to ensure the stability and strength of gripping. Jaw coefficient for FTG gripper type is 4 and that of the surrounding jaw is 1. The gripping force (F_G) and gripping torque (τ_G) is expressed as in Equation 7 and Equation 8, respectively:

$$F_G = W_e(1+G_s)\Gamma \tag{7}$$

$$\tau_G = F_G\kappa \tag{8}$$

Where

$W_e =$ Part/load weight (kg)
$G_s =$ Gravity acceleration (ms^{-2})
$\Gamma =$ Jaw style factor
$\kappa =$ Jaw length (m)
$G_s = 1.5 = 48ms^{-2}$ (a constant)

Figure-14 shows the torque required in the gripping test with a metal block ranges from 0.2kg – 0.6kg; generally, torque increases with increasing weight. G_s by object is not considered in Torque 1, while G_s is considered in Torque 2;it is noted that, for different W_e, Torque 2 increases at a lower rate than that of Torque 2. The gripper, categorized as friction jaw gripper (denotedas4), depends totally on the friction force to grip an object that does not fit into the shape of the gripper. Thus, extra work is needed to grip the object so as to avoid it from dropping. Effects of gravitational forces (G_s) need to be considered since the force is always acting on the object; the effect is different when the robot is moving horizontally than when it is moving vertically. As shown in Figure-14, thelowestforceis0.133Nm for a 100g metal block load, while the highest force is0.398Nm for a 600g load. This shows that the total torque varies with the weight applied on the gripper.

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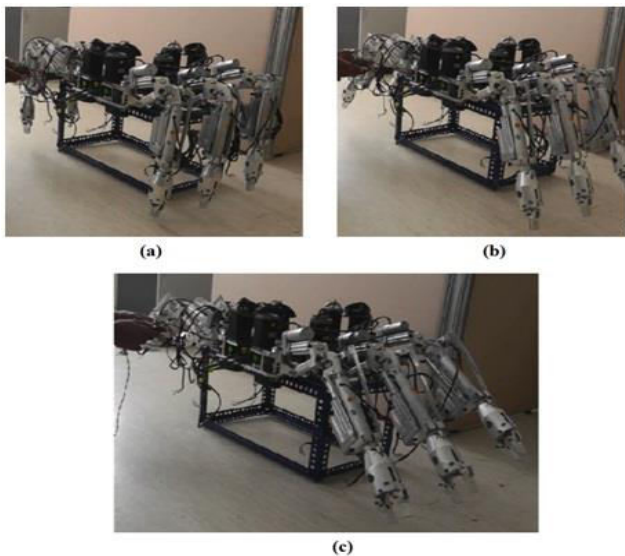

Figure-12. Hexaquad robot's synchronous leg moving test: (a) Standby and all legs close to the body, (b) All legs open to maximum extension, (c) all gripping opening and closing.
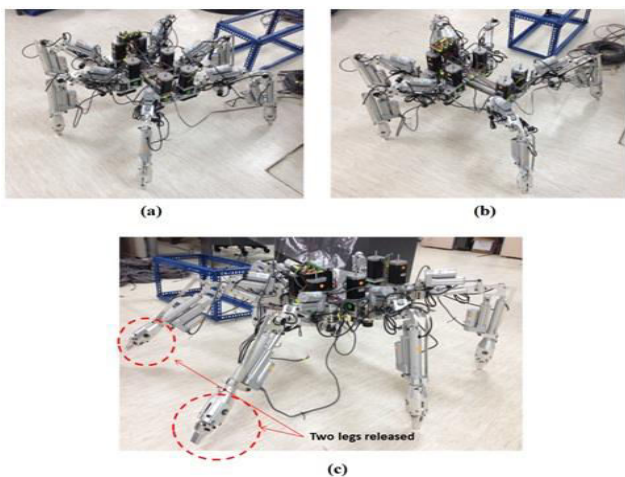

Figure-13. Hexaquad robot's standing test: (a)Hexapod mode standing test, (b) SLD transient transformation position test, (c) SLD Quadruped mode standing test.

Further tests are conducted using aluminum plates, square metal (aluminum) blocks and cylindrical metal (aluminum) blocks. As shown in Figure 15, the current required for the gripper to pick the aluminum plates is the highest; the current is positively proportional to the weight of the plates. On the other hand, the current needed to pick a metal cylinder is lower than that needed to pick the other objects. Approximately 0.26A is required to pick a 60g cylindrical metal block, whereas approximately 0.29A and 0.33A is required to pick a 60g aluminum plate and a 60gsquare metal block, respectively. In the case of the square metal block, the block did not slip during the gripping test.
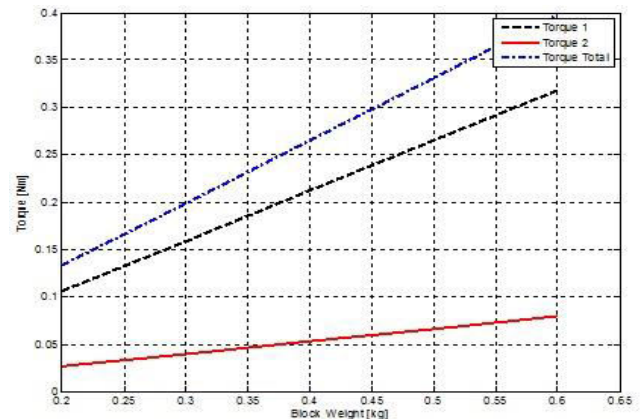
Figure-14. Sample of gripping testing for square metal block.

The small gripping area of the FTG exerts high pressure on the block, while maintaining a low pressure distribution. Hence, the pressure is focused on a small area, which contributes to the balance on gripper positioning. The actuator current's rate of change needed to grip a square metal block is higher when its weight is below; above 30g, the rate of change gradually decreases. This shows that, as the weight of square metal blocks increases, the frictional contact also increases(high gripping effectiveness).Thus, less current is required to grip the block compared to that of the other objects. However, as for the aluminum plates, more current is needed to pick the plates block compared to that of the other objects due to the decreasing gripping effectiveness.
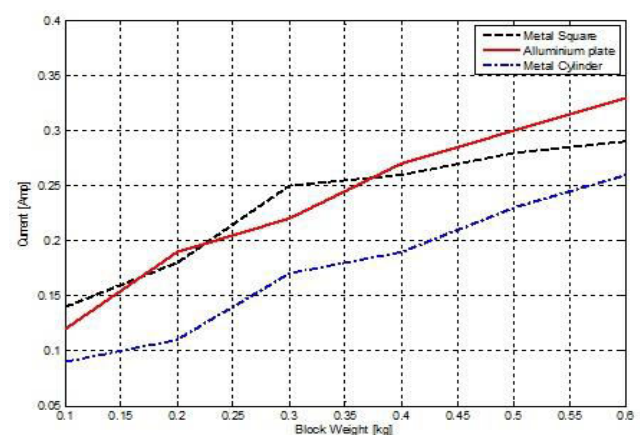
Figure-15. Gripping test for three different types of load/part versus actuator current.

The actuator current needed to grip a 50g cylindrical metal block is approximately 10% lower than that required for a 50g aluminum plate and a 50g square metal block. This is because the cylinder is placed exactly at the center force for the gripper, which is located at the center of the gripper's surface. Therefore, the cylinder can be held tightly even though its contact surface is smaller compared to that of the aluminum plate and square metal

block. Consequently, less vibration is produced during the gripping operation.

In addition, stress (Von Misses) and displacement deformation analysis was conducted on the FTG using Solidwork®, in which the test was constructed with the FTG lifting a50N weight. The analysis setting is as follows:

- Type of force: Concentrated force
- Surface: Gripper
- Fix body: Main block
- Material: Aluminum 6061 T4
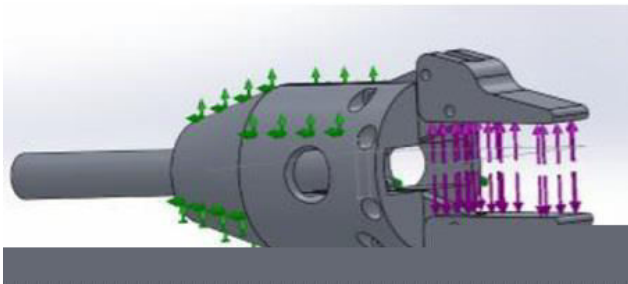
Figure-16. Stress analysis with 50N external force.

As shown in Figure-16, the fixed body (green arrow) is the area that remains static when force is applied and the 50N external force (purple arrow) represented the 5kg load gripped by the FTG. The displacement resulted when 50N force is applied to the surface of the gripper as shown in Figure-17. The red zone indicates where the most of the deformation occurred, while the blue zone is the less affected zone. The result also shows that the tip of gripper experienced major deformation of about 3mm once the load is applied. However, the tip did not receive the highest force compared to that of the other areas, except the area shown in red, because the tip is located away from the connector. The tip is still able to exert a 50N force even when the tip is elevated to its highest position. Connector plate 3 experienced fewer deformations of about 2mm as indicated in light blue. However, the main body did not receive any displacement as it is fixed to the frame structure. The result suggested that the applied force can be increased to over 50N as the red zone is still in the minimum range.
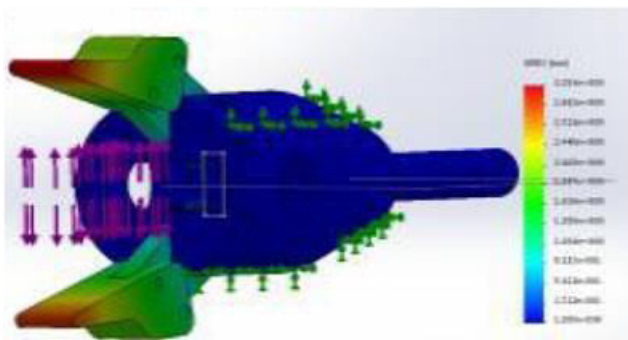
Figure-17. A sample of displacement result.

Furthermore the stress analysis is extended with Von Misses, as shown in Figure 18in which connector 1 and connector 2 are the most affected areas, while other parts of the gripper is still in minimum stress. 50N is the minimum force that corresponds to the 5kg load. The gripper is free from red zone area, which indicates the gripper is able to resist 50N without pushing to its critical phases.
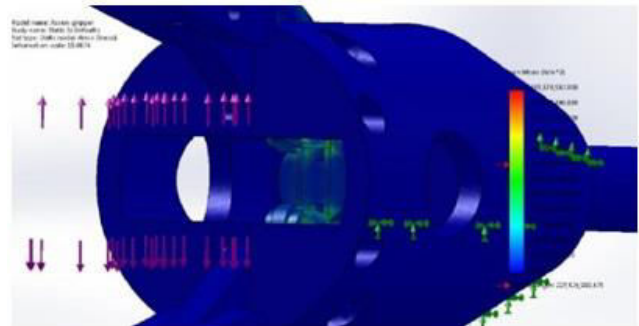
Figure-18. A sample of stress analysis (Von Misses) result.

The colored arrow indicator shows the yield strength value experienced by the connectors. High stress is concentrated at the connection between connector 1 and connector 2, shown in light green in Figure-18, as both connectors absorbed all the forces that were applied to the gripper. In addition, this analysis shows that the designed FTG is able to hold 50N forces without any breaking point detected. Moreover, FTG is able to maintain it shape, strength and position upon receiving the forces, surpassing the main objective to lift a 5kg load.

CONCLUSIONS

The development of Hexaquad robot from conceptual model to the actual model is presented in this paper. With reference to the fundamental testing and analysis, it shows that the selected actuators and motors are capable of moving all structures, including performing the holding torque on standing tests. Moreover, the gripping test and analysis also verify that the proposed FTG design is able to efficiently grip up to 5kg of load, without lifting the load. The drag current for each FTG is very low, which is proportional to the characteristic of the material. The next step in this research is to develop an optimized controller unit that could stabilize the motion of the robot's leg via vision camera feedback for autonomous movement. The target application will be in the areas of drainage and irrigation using collaborative control approach with other land and underwater robots.

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