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Design and Development of Hexapedal Robot to Achieve High Level of Mobility

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Article Info
Volume 83
Page Number: 179 - 188
Publication Issue:
March - April 2020
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Article History
***Article Received**: 24 July 2019*
***Revised**: 12 September 2019*
***Accepted**: 15 February 2020*
***Publication**: 12 March 2020*

Abstract

The main problem in current hexapod and hexapedal robot is the power source. In order to overcome the power supply problem in most of the robots currently used, energy generation would be a good option. Although, energy generation is feasible only for bigger robots, additional mechanical actuations are necessary in comparing with smaller robots to generate current in order to charge its power supply or battery. For motion in all types of terrain, hexapedal robot is a better option. Hexapedal robot which is also known as RHex will be an option which will be easier to replicate both biological based design and to implement battery charging and system performance monitoring method. The developed design is inspired closely to locomotion of cockroach and is classified as a hexapedal robot. After proper research and reference, C-shaped leg made from 3mm stainless steel sheet was designed and fabricated. C-shaped leg used in this design is the simplest version available for hexapedal robot. Developed design is fully implemented into operation using arduino based microcontroller (UNO R3). In order to monitor the developed design's performance, its battery level is monitored throughout using LabVIEW based GUI. As the robot operates, its batteries will discharge accordingly. Battery's current and voltage values will be displayed in control station through radio frequency data transfer. On the whole, the developed design is able to move well in numerous types of unplanned terrains (irregular surface) and is able to climb obstacle whose height is upto 70mm.

Keywords: *robotics, hexapedal robot, mechanical actuations, arduino.*

I. INTRODUCTION

Humans being the most complex organism in this world have one of the most advanced and adaptive type of locomotion. Nature has invented legs for most of the living organism while human invented wheels for better performance. Despite having a pair of leg to walk, arthropods are considered to have locomotion which is adapted for extreme conditions such as in forest. Arthropods have six legs which enables them to maintain their static stability though it does not aid in increasing their locomotion speed. Arthropods tend to show their versatility in case if one of their leg is damaged.

In development of mobile robotics technology, locomotion through all types of terrain remains a big challenge. Six-legged robots tend to show some drawbacks when used for locomotion in all types of terrain. Although hexapods have greater flexibility in locomotion, the motors used for this type of robots are not suitable for all types of surfaces. Furthermore, hexapods are well known for its applications where it is widely used in tasks which do not require speed. Hexapods still can climb

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elevation with respect to its size, in considerable slower pace. For applications which requires speed together extreme performance, hexapedal robots are the best solution in spite of wheeled robots. RHex robots are autonomous hexapod robot which has only one actuator per leg. This type of robot requires at least one motor for each actuator. This robot is the result of advanced dynamical system theory in order to mimic and improve the problems identified in animal locomotion. Robotics is moving towards an era where designs of the robot are recreated based on bio-mimic. This type robot has the capacity of speed exceeding its five body lengths each second and is able to travel through almost all types of terrain. Besides that, RHex robot can also swim as well as move through inclined surfaces without any compromise. Generally, RHex robots are also known as hexapedal robot.

Researchers (3) proposed that Sandbots is the new generation of legged robot which is able to move in world's trickiest terrain. In order to conquer sandy terrain, a natural sand crawler such as zebra-tailed lizard was analyzed. It was found that this lizard sinks its long bony toes deep into sand for its each step to launch from deep penetration where the sand there is more compact and stable. 'The effect, preliminary evidence suggests, is that the sinking enables the lizard to run as if on hard ground, allowing it to maintain speeds up to 75 percent of its pace on solid ground' (2). SandBot is also emphasized on other extreme terrains like disaster, warzone and high tendency of getting trapped in mud, snow and other unexpected elements. The challenge in building robots which is able to travel in all types of terrain is to keep speed as the controlled variable. SandBot was designed and constructed as an advanced version of RHex robot with mobility over many types of terrain. SandBot has better legs with accelerometers implanted on its legs where it sends information to its control system to detect different types of surfaces and auto-adjusts its locomotion accordingly. Its legs were designed to have maximum ability to grip sand and other morphing environment. 'With nature as guide, it is expect that robots will soon master some incredible new abilities' (2). Future advanced version of SandBot will be based on the ability of burying the robot into the sand inspired from lizard called sandfish. Sandfish opens up adaptation for robots to move beneath piles of debris, mud, snow, and to locate landmines in suspected areas.

Sprawl-Hex is a hexapod robot with adjustable body sprawl consisting of time trajectory of full body configuration and single leg ground reaction forces (6). Sprawl feature is adapted from cockroach's leg distribution. Different sprawl gives difference in area of contact of the robot's legs. The legs of SprawlHex are padded with shape memory foam which acts as damping and is covered with cover made of rubber in order to improve the traction of the robots leg with the terrain it travels. The slanting gait distribution is deployed to exhibit self-stabilization which arthropods like cockroach possess. The slanting arrangement of the robot's leg has exactly similar front-hip symmetry just like cockroaches. This motion gait is named as fore/aft movement. This gait is highly impractical and through considerations has to be given on the type of actuator used in order to respond accordingly to sudden change in speed. The sprawl locomotion of this robot is focused on flat horizontal plane it is least effective in unpredictable rough terrain. Researchers (6) proposed that SparwlHex can be further developed by concentrating more on its performance in highly harsh terrain. Besides that, the incompetency in power actuation opens up wide opportunity to improve SprawlHex with wider usage and features.

BigDog is legged mobile robot which is able to travel in rough terrain better than existing mobile vehicles. BigDog is designed to travel anywhere using its ability to carry additional load which makes this robot to be classified as unmanned load vehicle with the help of its 15Hp rated two-stroke internal combustion engine which enables this robot to carry additional load up-to 340 pounds.

Heat exchanger is mounted on the top of this robot, while a radiator is used to cool the combustion engine. Its 15hp two-stroke internal combustion engine propels hydraulic oil in high pressure throughout the system. After series of filter and distribution, the high pressure hydraulic oil is distributed to the robot's leg actuators. BigDog is able to run up-to 6 m/s. BigDog can recycle the energy absorbed from shocks during locomotion and reuses it. For further development, this robot should be able to travel in rougher and stepper terrain. Besides that, this robot should be accommodated with the ability to plan its locomotion by utilizing advanced terrain sensing in order to travel in tougher terrain. BigDog has the ability to balance itself in order to keep itself upright and is to be updated in the next version of the BigDog. Furthermore, a custom made muffler is to be associated with BigDog in order to reduce the noise produced by this robot.

Although numerous types of devices such as super capacitors and flywheels are considered for Energy storage system (ESS), batteries are the primary energy storage in EV (8). Based on the Peukert's formula, the rate of charging and discharging is thoroughly analyzed before coupling the entire subsystem together as a unit. The battery rate asymmetry, where both charging and discharge rate differs was considered in order to enhance the battery management procedures. By balancing the asymmetry of the battery, the energy efficiency is significantly enhanced. This balances the idle and cruise time of the charging migration in order to achieve the boost in efficiency. The total efficiency of this system shows that the energy efficiency is improved to 19.4% upon the deployment of mentioned enhancements.

Even though the study of balancing systems is currently considered a hot topic, there are no common procedures and metrics to evaluate their performance (1). Lithium-Polymer (LiPo) battery is among the best selection as storage device for EV. Though it is highly sensitive to overcharge and burst discharge rate. Battery Management System (BMS) is essential in order to enable state of charge (SoC) approximation, load disconnection ability, charging process effective management, pack current measurement and balance charging. BMS can be achieved through three level hierarchical platforms and each platform is controlled by module controller through remote communication bus. Power switches are used in order to balance each module by inducing it to battery. BMS system excludes particular battery module which gets fully charged before the rest of the pack in order to focus on the remaining of the pack. Similarly, fully discharged pack is excluded from the rest of the pack in order to avoid over-discharging. Balancing is done through passive balancing (bleeding), coupling switching buck/boost converter with super-capacitor or through isolated DC-DC converter module to cell. Individually super-capacitor with cell-to-cell balancing circuit shows energy transfer efficiency of about 90%. Methods employed in this research for battery balancing is slightly over 10 minutes through isolated DC-DC converter module-to-cell. Bleeding method provides constant balancing but it requires about six hours in order to complete its balancing task.

Cheetah uses a custom-made switching converter together with its motor driver. The motor driver is designed to work as a bidirectional buck-boost converter. It steps down the voltage in order to drive the brushless dc motor and steps up the voltage during regenerative braking in order to recharge the battery. Cheetah uses Microchip dsPIC30F6010 as its motor driving microcontroller. The motor driver is connected with LabVIEW based Real-Time controller in an i7 dual-core 1.33 GHz rated PC for testing purposes (12).

As discussed earlier, this project is done to solve the identified main problems found in the current hexapod or hexapedal robots. Improvements mentioned earlier are to implement the features in advanced current hexapods and hexapedal robots to a commercial and economic usage. The standard RC and other types of commercial hobby kit robots are powered by either power supply or rechargeable battery. The idea of recharging the robot's battery is practical in large robots; hence the concept of regenerative charging is feasible. If this concept can be fabricated in the commercial robots, it would be the solution for power supply problems in smaller robots. Furthermore, generating its own power is a sustainable idea where it does not require additional source of energy. As this project does not emit harmful substances to the environment, this robot will not possess any threat to ecosystem where it will be put to test. The success of this robot can be determined by its performance; especially on its ability to replicate adapted biological principle in its motion. With respect to the cost and the availability of resources, the actuators, microcontroller, batteries, sensors and other relevant spare parts are

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carefully chosen and designed accordingly. In order to recreate the battery charging as feedback to robot's locomotion, hexapedal design is chosen instead of standard hexapod robot. This robot has maximum usage of its actuator and motors. Hence, it is easier to charge the robot's battery when compared with hexapods. Following this concept the robot is to be fully autonomous with no OCU hardware used. Battery's performance such as rate of charging and discharging is proposed to be monitored through Simulink. As for this, the proposed system is built in order to meet the aim and objectives of this project.

After the introduction in section I, the rest of the paper is organized as follows. The implementation of the proposed method is detailed in section II. The experimental results are discussed in section III. Finally, the conclusion is concluded in section.

II. PROPOSED METHOD

The block diagram of the proposed system is as shown in figure 1. An independent power source 9V battery is used to power up only the microcontroller. Two rechargeable batteries are used for battery charging and switching application. Hexapedal robot's gait algorithm (17) will be stored in the microcontroller. Once the microcontroller powers up, the gait of the robot is controlled through the DC motor drivers. The motor drivers are powered by a rechargeable battery. The driver is interfaced with microcontroller in order to obtain the relevant logic for the motor's direction of rotation and speed control. The direction of rotational with respect to the gait algorithm is actuated by DC motors. The robot's leg is attached to the shaft of the actuators. Encoders fixed at the tip of robot's legs ensures the synchronous motion of tripod gait.

Table 1: Leg stride for tripod gait

		1	2	3	4	5	6
Tripod gait	First stride	High	Low	High	Low	Low	High
	Second stride	Low	High	Low	High	High	Low

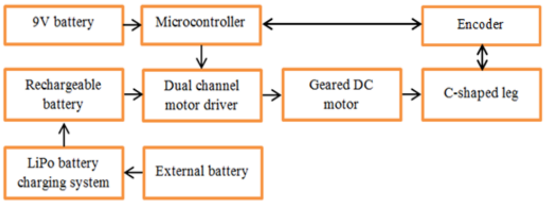

Figure 1: Block diagram of the proposed main system

In order to prolong the robot's operation time, this robot is proposed to be developed with dual rechargeable battery. When the primary battery is in use, the secondary battery will be deactivated. With help of voltage ratio (voltage divider) circuit, the primary battery's voltage will be monitored throughout. Once the battery reaches set point voltage, microcontroller activates the secondary battery and deactivates the primary battery as shown in figure 2.

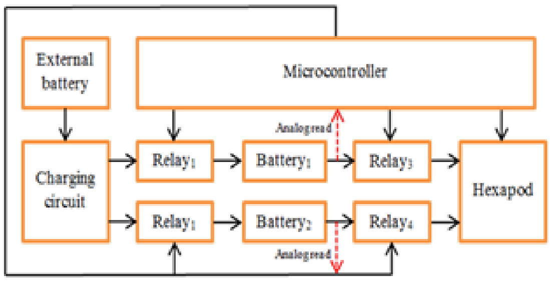

Figure 2: Block diagram of battery switching and charging system

Following that, the primary battery will be charged via a charging circuit. The procedure continues with charging of the secondary battery once its voltage reaches the set voltage. Switching between batteries and charging will be initiated using relays.

Tripod gait requires at least three legs in each stride. Legs in each stride are 180° out of phase. Tripod gait (18) can be further simplified based on the leg trio involved in each stride. Leg 1, 3 and 6 forms a group in its actuator rotates at the same time as shown in figure 3. The trio completes the first stride after its actuators rotate for a complete 360° as shown in table 1. Following that, the next trio which includes leg 2, 4 and 5 will repeat the similar pattern. Triangular pattern which is seen in the leg selection is to ensure the stability of the robot. At least one leg will be used in both sides while the locomotion takes place.

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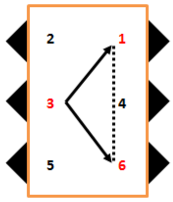

Figure 3: Tripod gait illustration

III. C-SHAPED LEG DESIGN

C-shaped selection is justified with its ability to imitate arachnid's leg movement behaviour which will be effective in unplanned terrain. Moreover, leg design is an essential move in order to prepare the hexapod for an unplanned terrain instead of using wheels. Besides that, the use of C-shaped legs in hexapod provides greater stability for the robot's structure both while on motion and at rest. C-shaped leg enables the robot to have steady manoeuvre as its surface of contact to the terrain is significantly wider than artificial spline legs. With help of high-friction rubber coating on the legs, robots can travel through hard terrains such as rocky surface. Considering structural stability and distributed leg performance, six C-shaped legs are finalized in this design.

Material used to fabricate these legs is stainless plate type 304. This type of stainless steel contains higher chromium and lower carbon composition. The effect of lower carbon composition can be observed as it minimized carbon carbide (CDC) precipitation which would likely occur due to inter-granular corrosion or welding. In contrast to its ancestor, type 302; this stainless steel does not require anneal to enhance improved corrosion resistance. Following that, this plate has high melting point which is between 1399-1454 oC. The most important factor which leads to finalize this material is its property against corrosion. This particular model unveils exceptional resistance to wide range of external exposures and is able to withstand oxidation until up-to 816 oC. CNC laser cutting method was used to model the leg's shape on the plate with small hole to attach the motor's driving shaft. CNC laser cutting provides clean and comparatively faster solution in fabricating parts. Although better, CNC waterjet cutting method is avoided as it is comparatively expensive and might not be effective to punch the required minute hole for actuator's mounting. As shown in the CAD design in Figure 5, the leg's dimension is as follow:

Table 2: Dimension of C-shaped leg

Height	70 mm
Width	40 mm
Thickness	3 mm

Height and width of the legs are kept in a way where the possibilities of collision between legs are minimal. The thickness of the leg is planned to be <5mm in order to allow the leg's motion in between an optocoupler (encoder). Selected optocoupler has space of 5mm in between its transmitter and receiver. In order to avoid possible collisions between the encoder and legs, the thickness of C-shaped leg is decided to be at 3mm. Following that, the hole to accommodate the actuator was fabricated exactly as the actuator's shaft shape. Motor's shaft has a dimension of 4x4 mm, hence the actuator will fit perfectly in the hole as shown in figure 6.

Figure 6: C-shaped leg fabricated using stainless steel material

The hexapod has perfect length in which it eliminates the possibility of collision between each leg. Figure 7(a) shows that the second leg in left will not by any chance collide with its front leg when it starts its gait. Figure 7 (b) shows the second leg's position once it reaches the half cycle of first set tripod gait while Figure 7 (c) shows that the second leg would not collide with the third leg in left once it rotates back to its home position.

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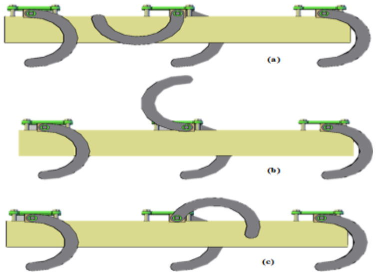

Figure 7: Leg motion (without collision)

Current cut-off circuit is mastered by an operational amplifier (LM324) as shown in figure 8. This op-amp cut off overcharge current from further charging the Lipo battery. Once the Lipo battery is fully charged, overcharging the battery will not be possible. LM324 acts as a guard and cuts off the battery's charging supply once the optimum threshold is achieved. Overcharge level can be setup by adjusting the 10k preset potentiometer in the overcharge cut-off circuit until an indicating LED lights up. Once the LED lights up, this refers that the battery is fully charged. This causes BC547 transistor to be switched on and grounds the ADJ terminal of LM317. Following this, the grounded ADJ pin of LM317 cut the supply from further charging the Lipo battery. This condition is remains locked with the help of 1kΩ feedback resistor which acts as a latch.

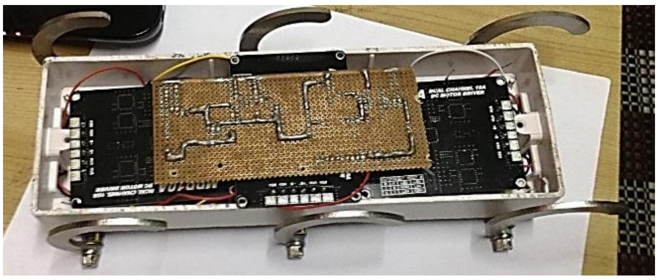

Figure 8: Hexapod with DC motor driver and Lipo battery charging and charge cut-off circuit

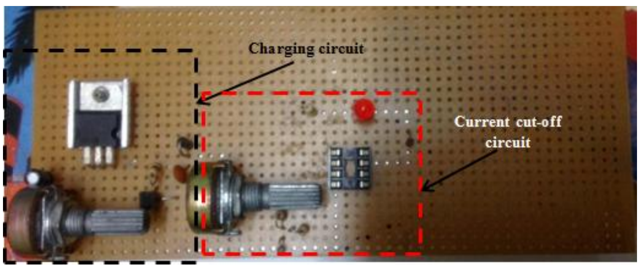

Figure 9: Charging and overcharge cut-off -off circuit

IV. WORKING PRINCIPLE – FLOW CHART

Figure 9 shows the flow chart of the proposed design. Once the microcontroller is powered up, the gait algorithm will be initiated. As per to achieve maximum mobility in this version of bio inspired robot tripod gait will be used in its locomotion gait. The PWM signal will be defined at the beginning of gait algorithm. The wiring connection between the microcontroller and DC motor drivers will be done. Both PWM and direction pins of the motor drivers will be interfaced with the microcontroller. According to the predefined algorithm, the direction of the actuator's rotation will be configured. If the predefined algorithm is achieved, tripod gait will be initiated. Tripod gait will ensure that the robot can move as desired hence maximum mobility can be seen. Since standard DC motors does not come with build in encoders, the actuator's rotation angle is hard to be controlled. The encoder will be used to notate that in each gait cycle, all three legs achieve exactly 360o rotation. Following the completion of the first cycle, microcontroller will initiate the next cycle's motion.

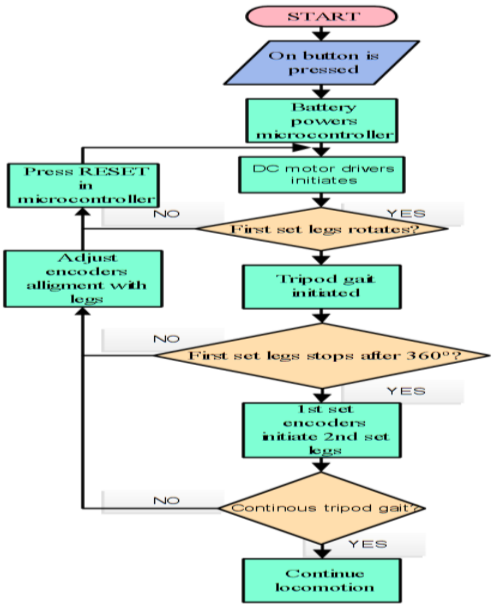

Figure 10: Flow chart of the proposed system

When the hexapod is powered, primary battery (B1) will run the robot for the designated tasks as illustrated in figure 10. A voltage ratio (voltage divider) circuit will constantly monitor the battery's supply percentage through the microcontroller's

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analog read function. Once the battery's voltage reaches a predefined set value, the microcontroller will activate the secondary battery (B2) and deactivates B1 through relay. Deactivated B1 will be charged through a charging circuit with external power source. The same procedure will be repeated to deactivate and charge B2 once it reaches the voltage set point. Selected battery will power up hexapod until the external supply for charging circuit becomes fully discharged.

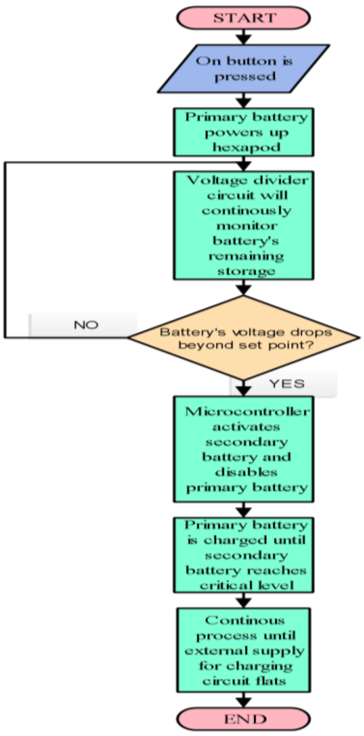

Figure 11: Flow chart of battery switching and charging system

V. EXPERIMENTAL RESULTS

Total of five testing are conducted in order to analyse the system's performance and to look for any possibilities of improvement. Tests conducted are closely related to the system's performance and gives way to analyse the discrepancy between system built and the objectives of this project. The tests conducted are as shown in table 3.

Table 3: List of tests conducted

Test	Target Area
Tripod gait test	Robot's leg precision
Incline climbing test	Ability to show extreme maneuver
Battery voltage monitoring test	Monitor the battery's performance
Adjustable voltage regulator test	Variation in output voltage based on R2
Overcharge cut-off test	Ensure that no overcharge occurs

Tripod gait test

Tripod gait test provides the hexapod with stability while maneuver and steady locomotion in unplanned terrain. This test is conducted in order to ensure that there are no possibilities of collision between legs and each set leg's motion is synchronous. The test is conducted by supporting the hexapod on higher surface and prevents the legs from touching the terrain (surface). Following that, hexapod's motion code is put to test in order to analyze the motion pattern of all six C-shaped legs. Besides that, this test is also to ensure that only the designated set of legs rotates at a particular moment. Hexapod at rest is shown in figure 11 and the leg motion pattern is shown in figure 12. Also, figure 13 & 14 shows the set of gait.

Incline plane testing

Incline plane testing is conducted in order to analyse the behaviour of this hexapod when there is sudden change in elevation in unplanned terrain as shown in figure 15. In a big picture, this hexapod can be commercialized as a load carrying robot in military purposes or even in Urban Search and Rescue (USAR) missions. A simple set up of elevation in range of 15^{o} to 45^{o} using plastic boards and elevation adjustments in form of porcelain vase. The finding for this testing is as follows:

Table 4: Elevation test results

Elevation (^{o})	Observation
15	Climbs without any difficulties
30	Able to climb but minimal slip occurs
45	Slips occasionally

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Battery voltage monitoring test

Battery's voltage monitoring test was done using the system's voltage ratio or voltage divider circuit. Two 30 kΩ resistors are used to ratio a fully charged 11.1V 2200mAh rechargeable Lipo battery as shown in figure 12.

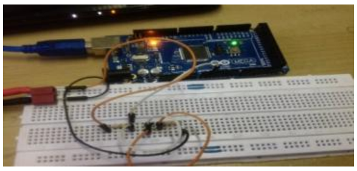

Figure 12: Experimental setup for battery voltage monitoring

The output voltage from the serial monitor feedback system is indicated as shown in the figure 17.

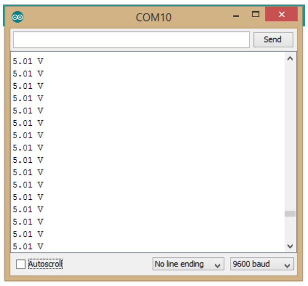

Figure 13: Serial monitor feedback

Adjustable voltage regulator test

Adjustable voltage regulator, namely LM317 sets the perfect input voltage in order to facilitate battery charging. Output voltage of LM317 is achieved by tuning a potentiometer to a desired value, namely R2. This test is done in order to identify the relation between R2 and Vin. This test is conducted by adjusting LM317's Vout to a bigger value, which in sudden may cause harm to the Lipo battery. This test still can be conducted even without a battery connected, though increase voltage value cause intense heating by LM317. Hence, precaution measures should be taken in order to avoid any sorts of accidents from occurring. Test finding is as shown in figure 18.

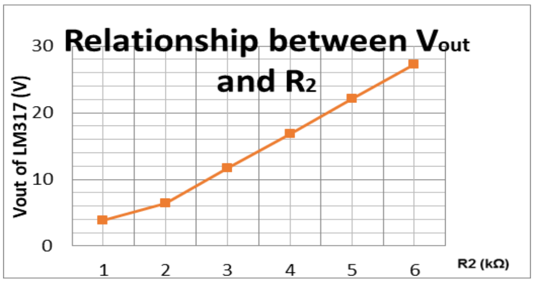

Figure 14: Relationship between Vout and R2

Overcharge cut-off test

A 11.1V 2200mAh rechargeable Lipo battery has three cells within. Each cell is rated at 3.7V. Theoretically, to charge a mechanism; the input voltage should be significantly larger than the mechanism's maximum rated voltage. Since single cell Lipo is rated at 3.7V, charging that cell would be possible from 4.2V onwards. 4.2V is used in this design as safety is the primary objective while conducting each test. For a 3 cell Lipo battery, safest voltage to charge the battery would be as follow:

$$V_{out} = (4.2 \times 3) + 0.6$$

$$V_{out} = 13.2V$$

In order to achieve 13.2V from LM317's output, potentiometer R_2 ($R_1 = 240\Omega$) should be sealed at:

$$V_{out} = 1.25V\,(1 + \frac{R_2}{R_1})$$

$$13.2 = 1.25V\,(1 + \frac{R_2}{240\Omega})$$

$$R_2 = 2.3k\Omega$$

The previous test can be used again in order to observe the behavior of opamp and state of the corresponding LED. The results are as shown in the table 4.

Table 4: State of LED with respect to Vout of LM317

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Resistance, R_2 (kΩ)	V_{out} of LM317 (V)	V_{out} + 0.6V	LED
0.5	3.8542	4.4542	OFF
1	6.4583	7.0583	ON
2	11.6667	12.2667	ON
3	16.8750	17.4750	ON
4	22.0833	22.6833	ON
5	27.2917	27.8917	ON

VI. SUMMARY

Summary of the tests done and inference is tabulated in table 5.

Table 5: Summary

Test	Inference
Tripod gait test	Hexapod's leg motion are precise
Incline climbing test	Hexapod slips in smooth surface
Battery voltage monitoring test	Battery's voltage discharge w.r.t time is accurate
Adjustable voltage regulator test	Vout increases with R2 (linear)
Overcharge cut-off test	Circuit cuts off voltage of more than 4.8V

VII. CONCLUSION

In conclusion, a hexapod robot based on adapted biological principle has been designed and developed. Research done on cockroach leg placement in unplanned terrain is analyzed as well in order to replicate similar behavior in this system. Based on cockroach's spline and tarsi, C-shaped stainless steel legs are designed and fabricated. The hexapod robot is implemented with Arduino microcontroller in order to control the hexapod and facilitate the entire system with high mobility. The performance of the system has been evaluated and inferenced that the hexapod's leg motion are precise, climbs on smooth surface, circuit cuts off when overcharged , exceeding 4.8V and battery discharges with respect to time accurately. On the whole, developed design is able to move well in numerous types of unplanned terrains (irregular surface) and is able to climb obstacle of height up to 70mm.

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