System Design for an Automatic Gait Selecting Low-Cost Wheel-Leg Hybrid Robot

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***Abstract*— All-terrain vehicles often use heavy mechanisms and sensors with huge computational power. In order to bring all-terrain capabilities to consumer robotics, which can be used in homes and offices, the cost and complexity of the robot needs to be reduced. This paper proposes a wheel-leg hybrid robot system using 8-bit micro-controllers which can traverse multiple terrains. The complete design from mechanical chassis to the gait selection procedure and experimentation has been shown.**

I. INTRODUCTION

In the field of exploration robotics, speed and manoeuvrability are the most important parameters for optimization. Covering more areas in less time and also covering spaces with motion constraints paves the need for a fast and easily manipulated drive. Mobile robots have many applications stretching from home entertainment and toys, through military applications, and search and rescue missions where they keep humans out of harm's way, to the exploration of other planets. Their greatest asset is their mobility. Non-mobile robots, like industrial robots, rarely leave the factory floor. So, the challenge to make mobile robots reach wider spaces at a low manufacturing cost in order to cater to a wider range of applications

As early as the 1870's scientists started to investigate how animals walk and run [4]. They even managed to develop some primitive walking models. These were primitive because they moved just as if they used wheels, moving their bodies in a straight path while the legs moved up and down in a mechanical sequence. In the 1950's it was realized that to get any real advantages from a walking machine over a machine with wheels the legs needed to be controlled individually [4]. The biggest advantage of using legs is the ability to choose where to contact the ground. While a wheel has no choice but to roll over and into every rock, hump or hole in its path, a leg can easily step over such obstacles.

However, the wheel has always been the easiest way to implement mobility in a vehicle, and has also been the fastest method of travel. Relative to speed it is also the most energy efficient way to travel. The implementation is often very simple, and does not require any advanced techniques such as vector controllers or additional joints to get the robot moving. Therefore, the wheel has since the early 1900 been very popular and it is used in many different robots [5]. On the other hand, having a platform with legs that are able to strategically choose contact points on the ground is a vast advantage over wheels in many ways. Not just because it can step over obstacles, but also because it can move smoothly over terrain. Consider a robot that moves one leg at a time and gently places it at a new stable position; the main body of such a robot would float forward smoothly like a boat even on really rough forrest like terrain. Another advantage is the ability to change direction of movement without changing the direction the body is facing. This is useful in tight spaces and creates a faster and more natural movement in places with a lot of obstacles. Wheels also have a tendency to slip on the ground when they lose traction. A leg on the other hand is much kinder to the surface it moves over. It can distribute its weight and even move its center of mass without changing the positions of its supports [6]. This advantage is desirable in cases like moving up or down a slope or stairs, or where there is a long distance between supporting objects to step on. The advantages are not just noticeable in rough environments. The urban society of today is in many ways adapted for legs, ask anyone in a wheelchair. Urban obstacles like stairs and doorsteps are often a problem for wheeled platforms. All these possible advantages come at a price though, the design will be more complicated and will have more moving parts. The actuators used today are still heavy compared to their power output. This often makes legged robots very heavy or weak, especially if they have many legs. Not only is the design of legged robots complex, but a large number of motors are needed to control them, which in turn require a heavy computation and power management circuit. The proposed design not only solves the problem of an efficient locomotion by hybridizing a wheel and leg motion in a single robot, it also defines a low cost, low power and low computational system architecture that can efficient control such a robot while allowing it to change gaits depending on the terrain.

II. SYSTEM DESIGN

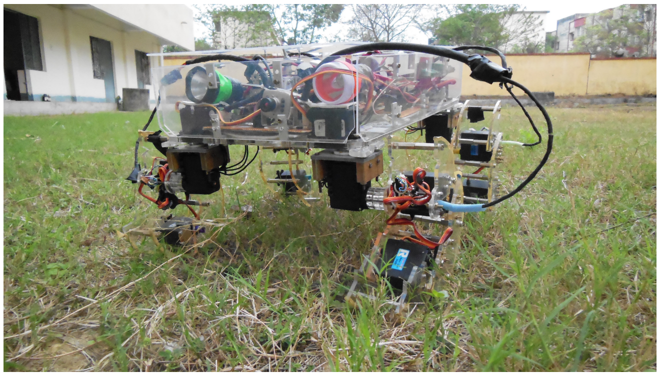

Fig. 1. Sirius-The Robot.

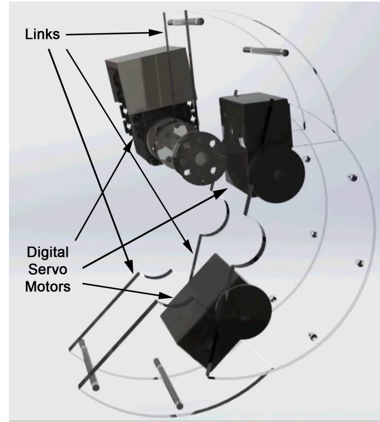

Fig. 2. Limb Design

A. Mechanical Design

The robot as shown in Figure1 aims at achieving a hybrid functionality of traversing in legged and wheeled modes with a single mechanical design. This calls for the requirement of a mechanical system capable of smooth transformation from one mode to another, without any compromise in performance in either form. In spite of the complexity of the requirement, it is essential that it be achieved in the simplest approach. [1]

Limb design: The limb design as shown in Figure 2 of the robot constitutes the most crucial mechanical aspect of the robot. The entire mechanical system was first designed part by part and then the assembly, with the help of the 3D-modelling and simulation software. In its crude form, the limb design comprises of a simple kinematic chain of three links- two in the shape of quarters, and another, a semi of a circle. The two actuators connecting these three links provide the transformation. These actuators are strategically positioned keeping the weight distribution of the limb in mind, so that when the limb forms a full circle in wheeled mode, the center of mass of the wheel, falls close to the radial center of the wheel thereby providing a dynamically stable rotation of the wheel. A triangular projection and a corresponding groove have been introduced to act as a passive locking mechanism when the limb is fully closed to form a wheel, and their design is such that they cause no hindrance during the transformation of the limb from one mode to another. A third actuator is introduced to provide the wheel rotation motion. A fourth actuator is attached to the limb to provide yaw actuation. The yaw actuation helps in providing better agility to the robot. Thus each limb comprises of 4 Degrees of freedom.

Base: To lower the weight of the system, rectangular parts have been cut out of the base such that it still retains more than enough strength to hold the weight of the necessary electronic components and itself. A stress analysis of the base with estimated reactions acting on it, helped support this. This perforation has helped reducing the weight of the base by about 22%. For deciding the dimensions of the robot, two parameters were optimized:

- Weight of the individual components in relation with the torques of the motors being used to drive them.
- The stability polygon consideration for the static stability resulted in an optimal ratio between the length and width of the robot which allowed for maximum possible step length considering other mechanical constraints (size of the wheels and angle restrictions of the motors).

1) Material Selection: The ideal material would be the one to have enough strength to bear the weight of the robot and also be light enough to help keep the weight of the parts minimal thereby reducing the load on the actuators. This helps in reducing the cost of the required actuators. In this particular robot, given the complexity of the limb design, the material should also support easy machinability. Aiming for a low cost solution, Perspex has been chosen as the suitable material for the mechanical parts as shown in figure 3 and figure 4. Over the conventional metallic materials like Aluminium which are heavier, Perspex holds the advantage of being over twice as thick for the same weight, given the difference in densities. This means that for the limbs, area of surface contact with the ground increases for the same weight and thus providing increased traction in both wheeled and legged modes. This adds to the stable locomotion of the system.

2) Motor Selection: A preliminary design was built using 3D modelling for the purpose of estimating the required torque at each of the joint and hence for the selection of a suitable motor. The material properties were assigned to the system, and considering the extreme positioning of the limbs, the maximum required torque at each joint was individually calculated. Given the necessity of controlled actuation to achieve smooth reconfiguration of limb as well as the gait in legged mode, servo actuators were the appropriate choice. The following are the motors used in the robot:

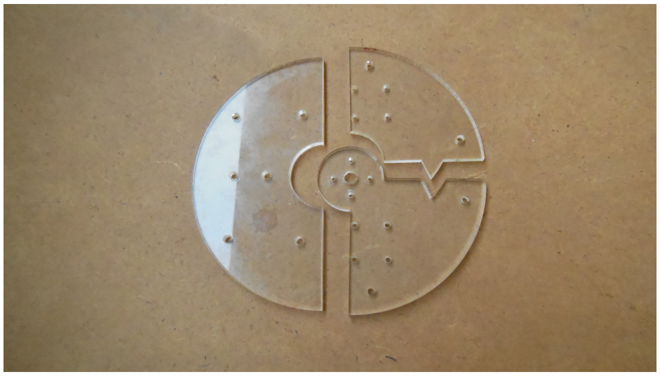

Fig. 3. Wheel Prototype

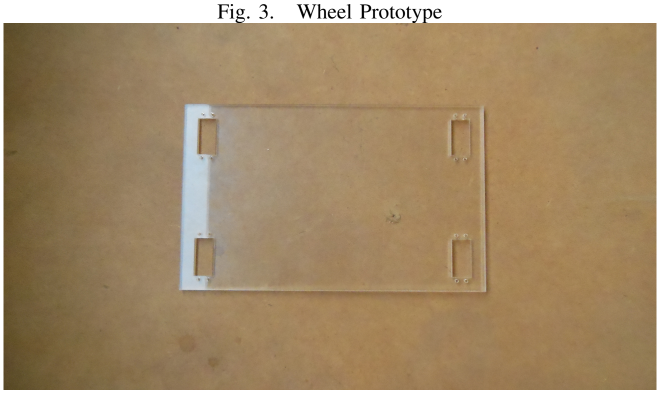

Fig. 4. Base Prototype

Component	Specification
Servo Motors	Torque: 16kgcm at 6V Stall Current: 1.5A Speed: 0.16sec/60deg
Dynamixel Motors	Model: ax 12A Operating Voltage: 9-12V No load speed: 60rpm Torque: 1.5Nm at 12V

The analog motors have limited range of motion. Hence they do not suffice at the joint which forms the centre of wheel, which in legged mode requires controlled actuation and free rotation in wheeled mode. Digital Servo motors Dynamixel AX12 have been chosen for this job as they can be operated in servo actuation or free rotation mode and also make a switch between the two whenever needed.

3) Manufacturing and Prototyping: The complexity of the limb design and also the demand of accuracy in machining the parts to ensure smooth transition between the two modes have led to the choice of laser cutting as the ideal machining, instead of conventional manufacturing techniques. The robot went through a series of manufacturing and prototyping before arriving at the final design. Limbs of various sizes were prototyped and tested for performance before finalizing the dimensions based on torque limitations. The final mechanical design of the complete robot is shown in Figure 5.

Slip rings: Direct wiring from the controller on the base to the servo motors of the limb, has been avoided. Instead, slip rings are used to bridge the connection so as to avoid entangling of the wiring harness when the limb has to perform continuous rotation about its axis during wheeled motion.

Fig. 5. Robot Mechanical Design

The robot description data is given below:

Robot	Description
Weight	3.5 kg
Length	36 cm
Width	24 cm
Height (Legged Mode)	24 cm
Height (Wheeled Mode)	18 cm
Closed Limb	12 cm diameter
Fully open limb	18 cm height

B. Embedded system Design

Embedded processing and power handling system is major part of the robot's construction which includes the on-board processor, motor controllers, battery, voltage regulators, touch screen controller and wireless communication module.

The robot was built in two stages; development and deployment. During development phase, inverse kinematic equations (angle calculations pertaining to all the legs) were solved on a laptop and sent via the wireless communication modules (XBee) to the robot. The on-board processors would receive the data sent by the inverse kinematic solver running on a laptop and provide target angular set-points to the motor controller module running on the embedded processor (As shown in Figure 6). This system helped in rapid development of various gaits because no hardware reprogramming was needed to configure the gait cycles. Various gait configurations were thoroughly tested in the development stage, the best gaits among them were chosen and fixed in the deployment stage (More details in section C). The sequential set-points of motor controllers corresponding to these gaits were programmed into the robot itself. Only the type of gait and the direction of motion was sent to the robot via a touch based controller (as shown in Figure 7). This was done to minimize the delays and to avoid transmission of redundant

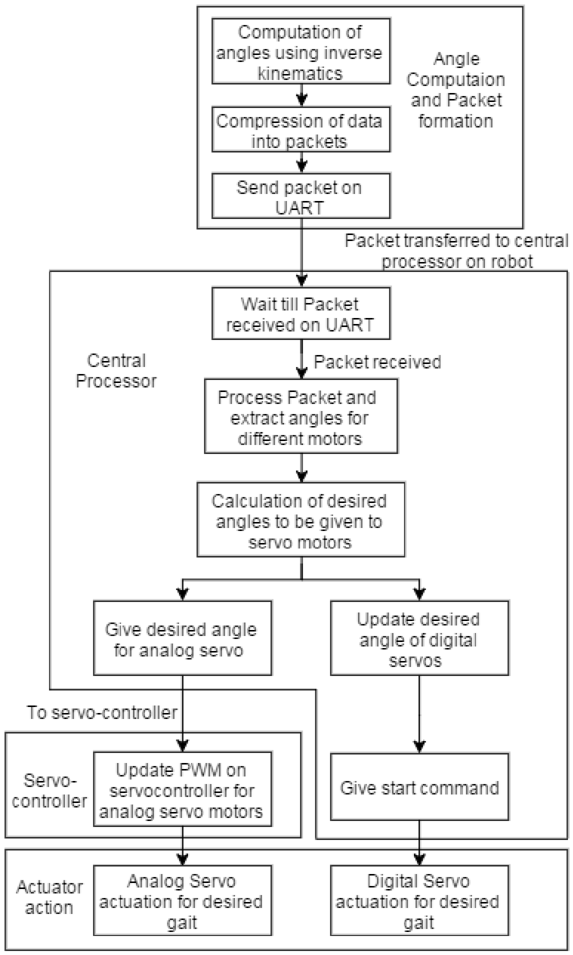

Fig. 6. Development Flow

information.
The designed robot consists of 16 servo motors working in synchronism. Both analog and digital servo motors are used in the construction of the robot. Analog servo motors have an advantage that they are cheap but they cannot be rotated continuously on the other hand digital servos are costly but they could be used for both servo action and continuous rotation. To keep the overall cost minimum, majority of the motors (12 out of 16) used are analog servos which are used at those specific positions where continuous rotation is not required while four Dynamixel digital servos are used at positions where both servo action and continuous rotation is required. To control the analog servo motors, a special hardware analog servo controller (RKI 1205) was used that received target angles of the twelve analog servo motors through UART and produced twelve different PWM signals to be subsequently provided as an input to the analog servo motors. Digital servo motors on the other hand are connected to the processor in a daisy chain fashion. They directly receive data via half duplex UART and perform required actions like rotating continuously (or by a particular angle). The main processor updates the target angles of all the digital servos in the first step, and then sends an execution signal in the next step. On receiving the execution signal, all the digital servos start moving simultaneously.
Actuation of 16 motors simultaneously needs a huge amount of current, which if not supplied might lead to lesser torque and undesirable behaviour. The operating voltage is also needed to be maintained between 4.5V to 7.5V for proper torque profile. To achieve this, a power circuit was designed with each analog motor having a separate voltage regulator LM317. In order to maintain current supply (peak value = 25A), a 3 cell LiPo battery was used with rating of 11.1V, 5000mAh, 20C. The battery voltage was within the operational range of digital servo motors, hence they were directly connected to supply from the battery.
The touch screen LCD (LCD-32PTU) was used to develop the (Human Computer Interface) HCI for demo purposes of the trained gaits. It uses UART to communicate to central processor. The various gaits and manual operation can be selected on LCD and corresponding information packets are sent to central processor to follow.

C. Gait Selection

Due to the low processing power on the target 8-bit processor, all the non-essential computation was shifted off board and pre-calculated data was used. For this, the static stability model of a quadruped was modified to use fixed step length parameters [2] . As shown in figure 8. 5 step positions were chosen which leads to 10000 possible states for the robot. Using the stability polygon for a statically stable gait and selecting only the states above a certain stability threshold, possible 1400 stable states to form the gait were calculated. For the static stable gait, following restrictions were imposed on the gait due to mechanical configuration and to rearrange the sequences:

- A maximum number of N states in a gait were defined as 9 and 12.
- The possible motions defined by each leg were limited.
- Number of states of the robot leg were kept to 5.
- The final and initial states of the gait should be the same.
- A particular configuration is not repeated in a single gait.
  By applying the above restrictions, Equation (1) gives the total number of gaits.

$$\frac{1625}{(1625-9)} + \frac{1625!}{(1625-12)!} \approx 5.25 \times 10^{41} \quad (1)$$

- Restriction was put on the number of body movements in one gait to be 4.
  Approximately 50 stable gaits and 10000 marginally stable gaits was obtained.
- A fixed duty cycle of 75% to avoid real time computational decision was used.
  On using this fixed duty cycle, the number of stable gaits came down to only 3.
- For each leg, the two lower servo motors have a fixed rotation angle of 90 degrees resulting in **One possible**

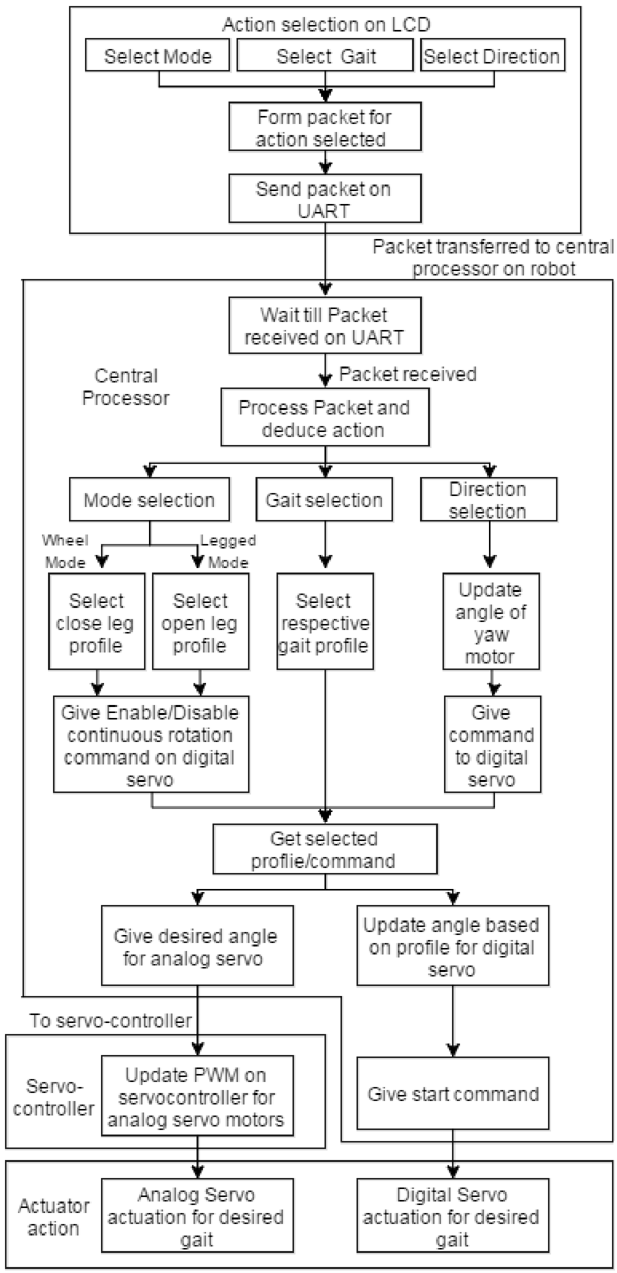

Fig. 7. Deployment Flowchart

Gait.

Then, two different gait models were designed using the choice of the third motor for each leg movement between the top servo motor and the dynamixel motor. These two led to the spider gait which was observed to be useful under heavy stress requirement and the dog gait which resulted in fast movement. The motion of each leg was defined along a predefined trajectory to allow pre calculation of data through inverse kinematics of both configurations (dog and spider) as shown in Figure 9. These angle values were calculated off-board optimizing between angle restriction (90 degrees for the two lower motors), stability and maximizing step length. These final angle values were coded to formulate the robotic configurations and the gait resulting in a lookup table for minimum computation.

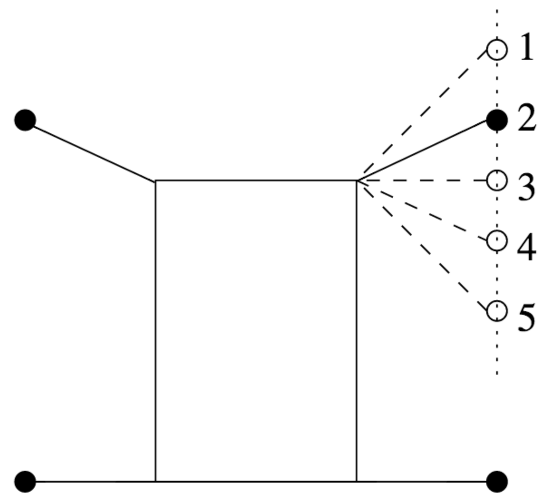

Fig. 8. Gait States

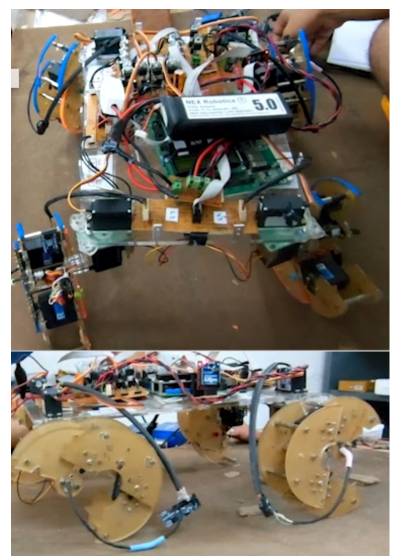

Fig. 9. Legged Gaits: Top one is Spider gait and Bottom one is Dog gait

Transformation into wheel mode as shown in figure 10 used fixed angles for the transition and which were found empirically. A step of 20 degrees resulted in an optimally smooth transition without very high jitters. The dynamixel motors and top servos (yaw) for each wheel gave the ability to experiment with multiple drive modes including Ackerman Drive, Differential Drive and near Omni Drive Control bottlenecked by the servos limit points at 180 degrees. This allows great manoeuvrability with the speed of a wheeled robot.

III. Future Work

Preliminary experiments were performed to classify terrains autonomously to change gait among the programmed set of gaits. Terrain classification was attempted by the

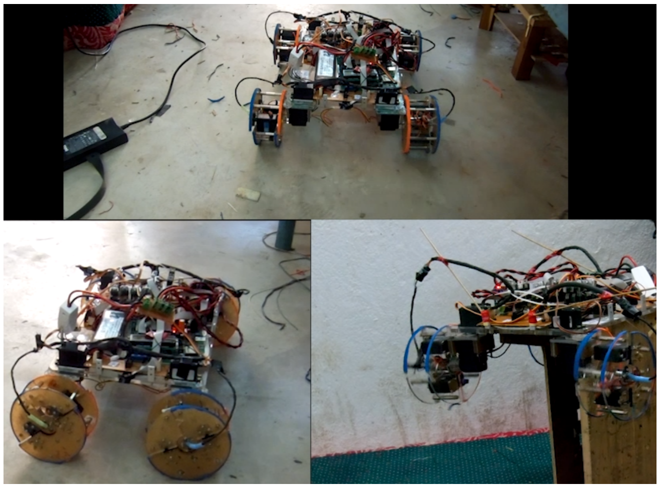

Fig. 10. Wheel Gait

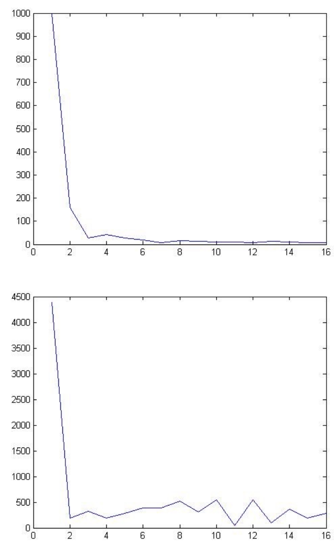

Fig. 11. 16-point FFT on accelerometer data in vertical direction for Plane and Gravel surface

following methods.

A. Fast Fourier Transform on Accelerometer

To perform autonomous transformation,16-point FFT is applied on the accelerometer data which helps in distinguishing between terrains on a 8-bit micro-controller. As shown in Figure 11, on a plane surface, FFT shows some peaks near low frequency region while on gravel the peaks shift towards high frequency region. The input is passed through a digital low pass filter with cut-off frequency determined experimentally.

B. Vision Based

In order to classify terrains [8], cmucam5 was mounted on the robot facing downwards which took images every 3 seconds. These images were then attempted to be classified into three classes for wheel gait, spider gait and dog

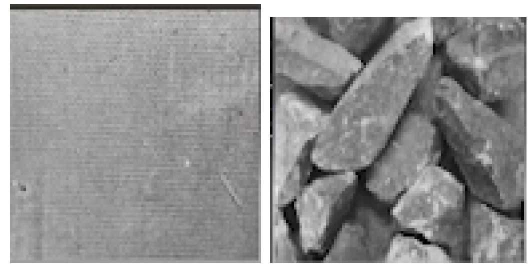

Fig. 12. Images of Plane and Gravel surface

gait. SVM was used to train images using local binary patterns(LBP) as the feature since they are easy to calculate using micro-controllers [7]. These features were trained on a computer using opencv and SVM post training parameters were noted and used in the classifier module in the central micro-controller. The camera would send images every 3 seconds to the central controller which would calculate the LBP and estimate a terrain according to which the robot will change gait. The experiment performed gave satisfactory results for two terrains shown in Figure 12 but more work is being done on improving this on more terrains.

IV. Conclusion

In this paper, the complete system design of an easily replicable low-computation wheel-leg hybrid robot that can traverse multiple terrains was presented. We confirmed the basic characteristics of the motion, which can be seen in the video submitted with the paper. The embedded circuit and gait selection experiment has been explained towards designing a low cost all terrain consumer robot. Experiments were also performed in detecting the terrain to choose gaits autonomously using two approaches, accelerometer and embedded camera, which showed satisfactory preliminary results paving the direction towards future work on the design.

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