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A Small, Insect-Inspired Robot that Runs and Jumps*

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Abstract **– This paper describes the latest additions to the Mini-Whegs™ series of small robots. These new robots are fully enclosed, measure 9 to 10 cm long, and range in weight from 90 g to 190 g. Mini-Whegs™ 7 weighs less than 90 g, but can run at over three body-lengths per second and surmount 3.8 cm high obstacles. The most recent iteration, Mini-Whegs™ 9J, incorporates fully independent running and jumping modes of locomotion. The controllable jumping mechanism allows it to leap as high as 18 cm.**

Index terms – Biologically inspired robotics, legged vehicles, micro-robots, reduced actuation.

I. Introduction

Small mobile robots are useful in a variety of applications. They can perform in hostile environments and outmaneuver larger vehicles in confined spaces. Small robots can be useful for covert missions or for rescue operations. Large groups of small robots provide redundancy in exploration missions. Small mobile robots are also appropriate for insect inspired research since they interact with the environment at a similar scale as large insects.

Existing small robots are often limited in mobility due to external power supplies, excessive weight, small wheels, or other constraints. Insects face the same scale issues as small robots, so they can provide inspiration for increased mobility.

Legs offer greater mobility than wheels over uneven terrain. Small robots imitating insect walking have proven to be quite successful. The cockroach, *Blaberus giganteus,* nominally walks in a tripod gait [14]. The animal's front and rear legs on one side move in unison with the middle leg on the opposite side of its body. At least three legs remain in contact with the ground at all times, forming a statically stable tripod. One small hexapod robot that moves using an insect inspired gait is iSprawl [4]. The tripod gait is achieved via a motor driving a dual crank slider mechanism to convert rotary to linear motion. The linear motion of the slider is transmitted to each set of three legs on the robot via cables sliding inside flexible tubes. The 15.5 cm long robot can move over 15 body-lengths per second (2.3 m/s) over smooth surfaces.

Traditional legged robots require many actuators and are difficult to control. Some attempts have been made by research groups to create simpler leg mechanisms with

Fig. 1 Mini-Whegs™ 9J, a 10.4 cm long robot that runs and jumps.

fewer degrees of freedom and fewer actuators. For example, the European Space Agency's PROLERO (PROtotype of LEgged ROver) has six spoke-like legs, each driven in a circular arc by six individual motors [6]. RHex also uses six motors to independently rotate each of its spoke-like legs, but its design incorporates compliant legs [11].

Whegs™ (patent pending) takes the idea of reduced actuation one step further. A single drive motor powers four or six multi-spoked appendages called wheel-legs [9][10]. Neighboring pairs of wheel-legs are offset by 60º, yielding a nominal alternating diagonal gait in a vehicle with four wheel-legs or a nominal tripod gait in the case of a vehicle with six wheel-legs. The spokes allow Whegs™ to climb over larger obstacles than a vehicle with similarly sized wheels. The use of a single large drive motor provides a high power-to-weight ratio, making Whegs™ highly energetic, and compliant drive components enable passive gait adaptation over irregular terrain.

In addition to walking, many insects jump to escape from predators, to increase their speed across land, or to launch into flight. Some insects, like bush crickets, have long rear legs that provide leverage, enabling them to jump longer distances than insects of comparable mass with shorter legs [2]. The froghopper, *Philaenus spumarius*, on the other hand, has relatively short legs, but can outperform any other jumping insect relative to its body length [1]. Before a jump, the froghopper rotates its rear

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legs forward until they are parallel with the body, with the femora tucked between the middle legs and against the body. A ridge on each femur engages with a protrusion on the coxa (hip joint), locking the femur in place. The muscle that powers the jump can then slowly contract while the leg remains immobile. When enough energy is stored in the muscle, the femur disengages from the coxa, snapping quickly outward with a force 414 times the body weight of the insect.

One robot that uses jumping as a secondary mode of locomotion is Scout [12]. Scout is a cylindrical robot 4 cm in diameter and 11 cm long. Wheels at either end of the cylinder provide the primary mode of locomotion. A triangular spring-steel foot between the wheels stabilizes the robot during normal rolling, but can be retracted and released by a small winch causing the robot to jump up to 20 cm high. The cylindrical shape and low ground clearance of the robot limits the mobility of the robot over uneven terrain, so the jumping ability adds valuable mobility.

Mini-Whegs™ are a series of small robots approximately 9 cm long that use wheel-legs for locomotion [8]. They demonstrate that the concept works well at a small scale. These robots have run at sustained speeds of over 10 body lengths per second and have climbed obstacles higher than the length of their legs.

A Mini-Whegs™ was built previously to demonstrate a jumping capability in the platform [7][8]. Like the froghopper, Mini-Whegs™ 4J slowly retracts a jumping mechanism, which is then released suddenly. Energy for each jump is stored in a linear spring that stretches as the jumping mechanism is retracted towards the body. Mini-Whegs™ 4J can jump over two body lengths high (22 cm). However, jumping and running are not independent in this prototype vehicle. The robot repeatedly runs and jumps with no control mechanism. Additionally, since the purpose of the prototype was to prove the jumping concept, steering and radio control components were left out. This paper describes the development of a fully controllable running and jumping Mini-Whegs™.

II. Methods and Design

The overall design goals for the Mini-Whegs™ series are functionality, simplicity, compactness, and durability. All Mini-Whegs™ are similar in size and weight, and have two axles with two three-spoke wheel-legs attached to each. A single propulsion motor drives both axles. The chassis consists of a rectangular frame that houses the main systems, including the drive train, steering components, batteries and the onboard radio control components. This section describes the design of the various sub-systems that make up the two most recent Mini-Whegs™: Mini-Whegs™ 7 (Fig. 2) and Mini-Whegs™ 9J (Fig. 1). Table 1 compares these new designs with those of previous Mini-Whegs™.

A. Legs

Like larger Whegs™, Mini-Whegs™ employ several three-spoke appendages called wheel-legs for locomotion. For the sake of simplicity and reduced size, the Mini-Whegs™ series of robots uses just four wheel-legs, which results in an alternating diagonal gait. These appendages have been redesigned several times to improve the mobility of the robot.

Fig. 2 Mini-Whegs™ 7 can climb obstacles 25% greater in size than the length of each leg spoke.

The first Mini-Whegs™ used wheel-legs consisting of a Delrin® hub and wire spokes. Later versions used a design similar in size and shape to the first design, but machined entirely out a single piece of Delrin®. The all-Delrin® design results in legs that are somewhat flexible, much lighter, and require no assembly. Although bare spokes are excellent for reaching onto large obstacles, the sharp tips of the legs catch in rough surfaces, such as carpet and offer almost no traction on hard, smooth surfaces.

Later leg designs add a short foot to the end of each leg spoke [5]. The foot consists of an arc segment with a radius equal to the length of the leg spoke. The length of the foot, described by the length of the arc in degrees can vary between 0° and 120°, from bare leg spokes to a complete wheel. A shorter foot yields better climbing ability, but is harder to control. A foot length of 25° provides a good compromise between smooth operation and obstacle clearance capacity. The foot is short enough that it does not extend far past the front of the body when in contact with the ground, so the vehicle's climbing ability is minimally affected.

The addition of the foot completely eliminates previously observed somersaults and removes a great deal of undesirable springiness from the walking motion,

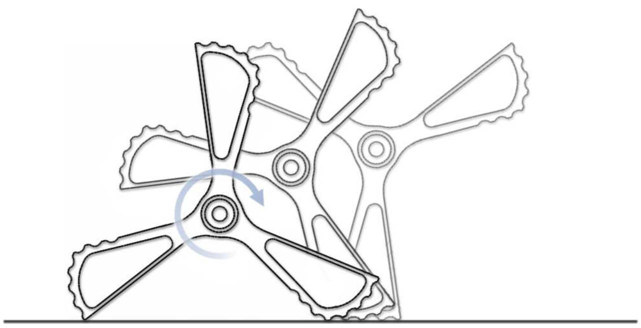

Fig. 3 Diagram illustrating the new leg and foot design used in Mini-Whegs™ 7 and Mini-Whegs™ 9J.

making the robot much easier to control. However, the exposed toe of the foot can still catch on tangled objects such as string, cable, or vegetation. Also, the heel of the foot where it attaches to the spoke is squared off. This extends the reach for climbing as long as possible, but also creates a jarring impact every time the leg impacts the ground.

In order to solve traction and tangling issues, and to further improve walking smoothness, the wheel-leg shape for Mini-Whegs™ 7 was completely redesigned. It has since been adapted at a number of different sizes for three Whegs™. Elements of the leg shape and construction have also been adapted for mid-size and full size Whegs™.

The heel of the foot is designed to be parallel to the ground when it first makes contact. The radius of the foot arc then increases toward the full length (Fig. 3). Thus, the impacts onto a sharp corner are eliminated. The contact patch of the foot is wider to add traction. Small ridges are also cut into the foot and back of the leg to add gripping surfaces. These ridged surfaces are then coated with Plasti Dip®, a rubbery plastic coating usually used for tool handle grips, to improve traction on hard, smooth surfaces.

A thin spar of material connects the toe of the foot back to the hub of the wheel-leg, eliminating some of the tangling in foreign objects, especially while moving backwards. However, during machining of this improved design, it became apparent that the spar was too thin and flexible by itself. It broke easily and the stress concentrations at the roots of the ridges along the leg and foot caused part failures. These problems were remedied by adding some extra thickness to the foot and leg, while also adding a thin web of material filling in the space between the leg and toe-hub connection. Thus, there are no openings or extrusions in the final design, so problems with tangling are virtually eliminated.

B. *Steering*

In order to transfer power from the front axle to the wheel-legs spinning on the steering uprights, a small joint is required. Two intersecting degrees of freedom are required to allow the axle to rotate while it pivots to steer. Previous Mini-Whegs™ used a flexible shaft to transmit power to the front wheel-legs. A short length of spring tubing, or other flexible material, is attached to the ends of the driven axle. This flexible coupling is attached to a small hub that rotates in the steering upright and attaches to the wheel-leg. Unfortunately, small springs unwind too easily, and flexible shafts fatigue and break. A more durable steering joint is required for a successful Mini-Whegs™.

In Mini-Whegs™ 5, flexible materials were abandoned entirely. The required two degrees of motion are achieved through a pinned ball and cup, which together comprise a simplified universal joint. A steel ball machined onto the ends of the front axle fits into a brass cup that forms the rotating hub to which the wheel-leg is attached (Fig. 4). The cup is held in place by a bearing in the steering upright. A slot is cut into the cup. A short pin through the center of the ball slides in this slot, providing the first degree of freedom. The cup can also rotate around

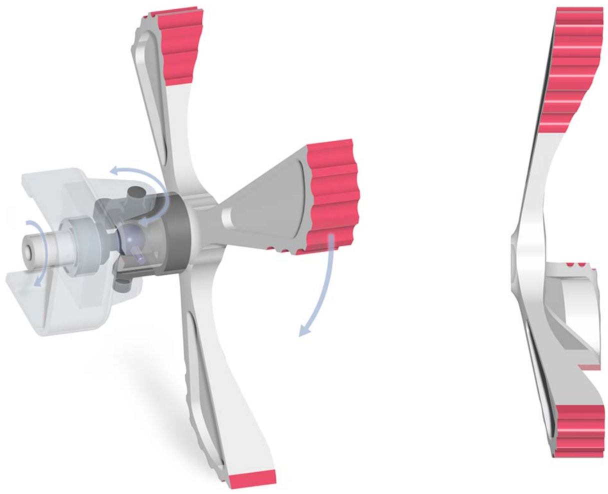

Fig. 4 Renderings of the current Mini-Whegs™ steering mechanism (left) and the new splayed leg design (right).

the pin, providing the second perpendicular degree of freedom. When the pin pushes against the side of the slot, the cup rotates with the driven axle, so that the wheel-leg can rotate as well. Careful design of the ball and cup allow the steering to pivot ±30º. This simplified universal joint is durable and reliable, but unfortunately the steel and brass also make the mechanism very heavy.

In order to reduce the weight of the steering mechanism, Mini-Whegs™ 7 does not use brass or steel parts. The driven axle consists of a hollow aluminum shaft that is threaded to accept two anodized aluminum ball studs. The cup that mates with the ball on the end of the axle is machined from aluminum stock. Since the ball stud has been anodized, galling between the cup and the ball is not an issue. Unfortunately, because the ball stud was not specifically designed for this application, somewhat less steering travel (about ±25°) is possible. However, the different geometry also allows the cup to be slightly smaller, so it can fit into a smaller space. This reduces the overall width of the robot. The hollow shaft and aluminum components drastically reduce the weight of the mechanism.

The steering uprights pivot around the same axis as the ball and cup universal joints. In Mini-Whegs™ 7 and Mini-Whegs™ 9J, a 48-pitch nylon rack acts as the control arms to pivot the steering uprights. Small supports inside the body of the robot keep the rack from bending away from the nylon pinion attached to the steering servo. Mini-Whegs™ 7 uses a 5.6 g “pico” servo for steering, while Mini-Whegs™ 9J employs a smaller 4.4 g servo to save space and weight.

C. *Drive Train*

Previous Mini-Whegs™ robots all used 13 mm Maxon motors to drive the Whegs™. Maxon motors with planetary transmissions are well suited for these small robots since they provide high torque at high speeds. However, the metal gears make them quite heavy. Also, Maxon motors draw high current, which means that battery selection for powering the motors is limited. In Mini-Whegs™ 7 a micro-servo modified to rotate continuously replaces the Maxon motor. By replacing the potentiometer in the servo circuit with a pair of constant resistors, the circuitry creates a speed controller instead of a position controller. The MPI MX-50HP servo was selected for its high power to weight ratio, small size, and relatively high speed. It was estimated that the servo would be able to provide similar speeds to the Maxon motor at about half the torque. Since previous Mini-Whegs™ robots did not lack torque, the lower torque figure was expected to be a valid trade-off for lower mass and cost.

Most previous Mini-Whegs™ robots used a pair of stainless steel 0.1475-inch pitch chains and aluminum sprockets to connect the drive shaft to the axles. To reduce weight and ease assembly, a 0.1227-inch pitch acetal chain with acetal resin sprockets was selected for the new design. To save further room and weight, only a single chain, wrapped in a "U" shape around the drive shaft sprocket, was employed.

Mini-Whegs™ 9 incorporates many of the same drive train elements as Mini-Whegs™ 7. The same modified servo is used as a drive motor, driving a single acetal chain with acetal sprockets.

D. *Electronics*

Previous designs used a custom radio control receiver designed for ultra-lightweight model aircraft. While very small and light, the receiver was expensive, hard to obtain, and had unreliable electrical connectors. To reduce costs and improve the availability and reliability, a different receiver, the Hitec "Feather" four-channel receiver, which offers standard size connectors, was selected for use in Mini-Whegs™ 7.

Standard radio control components, such as the servos and receiver being used, require between 4.8 and 6 Volts to run properly. The high torque, high speed motors driven directly by the batteries via a speed controller also require relatively high current, on the order of 100 mA or more. Most readily available small batteries cannot meet both the voltage and current delivery requirements. There are a few cells, primarily designed for camera applications, that do meet the needs of Mini-Whegs™ robots. These include the 3V CR2 cells used on previous designs. However, since 2 cells are needed to reach 6 Volts, a significant portion of the size and weight of the robot is taken up by those batteries. Thus, the smaller, 6V 2CR-1/3N battery was selected for testing. Brief unloaded tests with two servos and a receiver indicated that the battery was capable of powering the robot. Later tests with the completed Mini-Whegs™ 7 showed that, while the robot was able to move with the smaller battery, the higher current delivery capacity of the CR2 cells led to much higher mobility.

In order to conserve weight and space, Mini-Whegs™ 9J uses Cirrus Micro-Joule radio control components that are lighter and smaller than the Hitec receiver used in Mini-Whegs™ 7.

E. *Chassis*

The body of Mini-Whegs™ 7 was designed to reduce weight and to make the robot easier to assemble by reducing the number of fasteners. Previous designs used a pair of Delrin® rails connected by aluminum cross-members, held together with 16 tiny steel screws, to hold all the components in place. The steering components, radio receiver, and drive motor were held in place with even more screws. The new design consists of upper and lower shells that hold two side rails in place. Delrin® was once again chosen for its good strength and machinability. In this case, all the chassis components are hollowed out significantly to reduce weight. Four nylon screws hold the two halves together. Components are trapped vertically beneath the shells, and held in place horizontally by short internal walls, so no extra fasteners are required.

The chassis for Mini-Whegs™ 9J incorporates the same weight reducing features. The top and bottom shells are machined from ABS in order to reduce weight even further. The shells include holders for the steering servo, batteries, drive servo, radio control components, and jumping mechanism motor. The side rails are machined from Delrin® because of the higher bearing loads encountered due to the axles of the jumping mechanism. The batteries are mounted vertically on either side of the servo, protruding through the top chassis shell. This reduces the length of the robot by over 12 mm. A separate battery lid fits over the protruding batteries and fastens to the shell with two screws. The separate lid allows the batteries to be changed more easily than in other versions.

F. *Jumping Mechanism*

The four bar mechanism in Mini-Whegs™ 4J consists of thin titanium links attached to solid aluminum shafts with steel screws and washers, and brass bushings to reduce friction at the joints. While titanium is stronger than aluminum on a per mass basis, it is more expensive and denser. Since the links cannot be machined to use much less material than they already do, using aluminum would actually reduce the weight of the links. In order to add needed stiffness, a single or double rib was added to the links to create a "T" or "C" shaped cross section. The

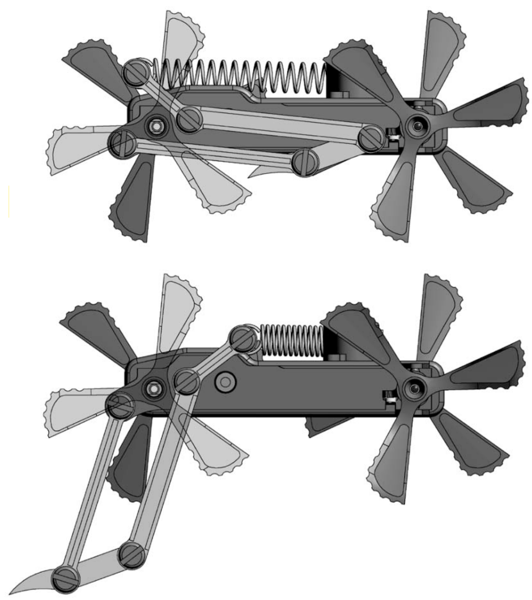

Fig. 5 Side view renderings showing the jumping mechanism of Mini-Whegs™ 9J in retracted (top) and released (bottom) positions.

resulting links are light, easy to machine, and much less expensive than those made of titanium. Using a hollow aluminum shaft with larger nylon screws further reduces the weight of the mechanism. The large diameter of the assembly screw allows the shafts to be thin-walled, while the large heads eliminate the need for washers to keep the screws from pulling through the holes in the links. Thin Teflon® washers are used to reduce friction between the screws and the links. The four-bar jumping mechanism used in Mini-Whegs™ 9J is illustrated in Fig. 5.

In order to separate jumping from running, another actuator must be added to the robot. While several methods were considered, including the addition of a solenoid-activated clutch between the drive motor and a secondary transmission, the addition of a completely new motor for jumping was determined to be the most viable solution. The torque requirements for extending the spring on Mini-Whegs™ 4J were measured experimentally using suspended weights to cancel out the torque created by the spring. From the torque requirements, it was then possible to select a larger motor and transmission.

The Maxon transmission with the highest allowable intermittent torque, while staying at suitable size, is a 13 mm, 1119:1 planetary metal gear transmission. This is a much smaller transmission ratio than the 18,545:1 reduction from the double transmission used in Mini-Whegs™ 4J [5]. The larger load on the motor necessitated the selection of a larger 2.5W motor instead of the 1.2W motor previously used. However, the reduced gear reduction has benefits as well—the wind time is about 10 times faster, and eliminating a second transmission also reduces friction, making the robot more efficient.

The four-bar jumping mechanism has only one degree of freedom, so only one actuator is necessary to retract and release the linkage. In order for the energy stored for each jump to be released rapidly and in a repeatable manner, a tension spring is used. A "slip-gear" mechanism is used to stretch and release the spring.

The slip-gear consists of a pinion attached to the output shaft of the jumping motor/transmission that drives a gear attached to one link of the four-bar mechanism. The pinion is a 12-tooth, 32-pitch spur gear that has 8 teeth removed, leaving one section of 4 teeth intact. The driven gear attached to the jumping mechanism is a larger 18-tooth gear. As the pinion rotates, its teeth engage with the driven gear rigidly attached to the four-bar. This rotates the mechanism into the body of the robot stretching the spring until it is fully extended.

If the pinion continues to rotate, the teeth are no longer engaged with the driven gear. At this point, the driven gear is free to rotate independently of the pinion, so the spring contracts suddenly, releasing the jumping mechanism to its unloaded position and causing the robot to jump. As the pinion rotates even further, the teeth reengage, rewinding the mechanism for the next jump. This system requires no active input for control; it can simply wind and jump repeatedly. By turning the Maxon motor that drives the slip gear on or off, the position of the jumping mechanism can be controlled. The large transmission on the motor is not back-drivable, so the mechanism is held in place even when the motor is powered off. Additionally, the 3:2 gear reduction of the slip-gear mechanism itself increases the torque at the jumping mechanism joint, compensating for the reduced gear reduction in the transmission. The 18-tooth gear only rotates through about 100° to retract the jumping mechanism, so about half of the teeth on the unused side of the gear are removed to reduce weight and improve clearance between the gear and the rear axle.

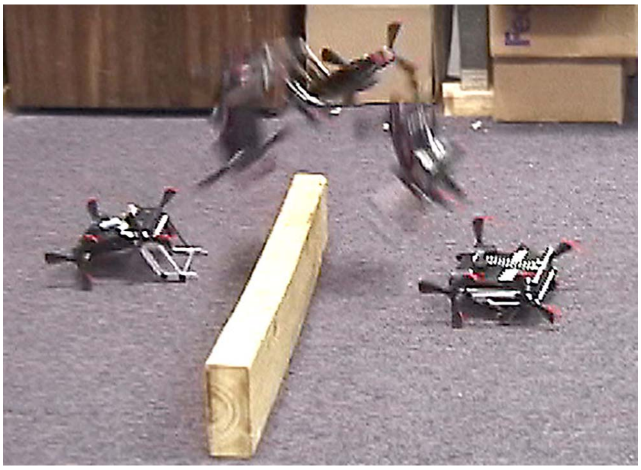

Fig. 6 Composite of video frames showing Mini-Whegs™ 9J jumping high over a 9 cm barrier.

III. Results

The primary advantage of wheel-legs over wheels is increased mobility on uneven terrain. Because of the three-spoke geometry, a Mini-Whegs™ robot can climb over obstacles up to 1.7 times as tall as the leg length. An obstacle less than one radius high easily stops the same robot fitted with wheels of the same radius.

Table 1 summarizes the recent design evolution of the Mini-Whegs™ series by comparing the sub-system masses of four robots. In particular, from this table we can see why so many design changes were necessary in order to obtain a fully controllable jumping robot. If a 44.5 g jump motor and the jump mechanism used in Mini-Whegs™ 4J was added to Mini-Whegs™ 5 the resulting robot would weigh at least 289 g, nearly 50% more than the proof-of-concept. Such a robot would need a much stiffer spring to jump and a larger, heavier motor to wind the spring.

TABLE 1

COMPARISON OF SUB-SYSTEM MASSES FOR FOUR MINI-WHEGS™

	M-W 4J	M-W 5	M-W 7	M-W 9J
Chassis	31.3	39.7	30.2	33.7
Drive Train	27.1	36.1	9.7	11.4
Wheel-legs	6.4	6.4	11.1	15.8
Batteries	22.2	22.2	9.0	22.2
Drive Motor	31.5	31.5	9.4	9.4
Steering Components	—	19.0	9.5	8.1
Electronics	—	8.5	9.9	7.8
Jump Motor	—	—	—	44.5
Jumping Mechanism	81.0	—	—	38.5
Total Mass (g)	**199.4**	**163.3**	**89.5**	**191.4**

A. *Mini-Whegs™ 7*

The chassis of Mini-Whegs™ 7 measures 5.4 cm by 8.9 cm. The final weight of the robot is 90 g with a 6V 2CR-1/3N cell, or 108 g with the two 3V CR2 batteries. While not as fast as previous versions, Mini-Whegs™ 7 is still able to move at almost four body lengths per second with the more powerful cells. Obstacle climbing ability is on par with earlier designs (Fig. 2).

Testing with an external power source showed that the continuous drive servo was capable of higher performance than was seen with the single 6V cell. Thus, a makeshift rig was assembled to attach a pair of 3V CR2 cells to the top of the robot. Top speed tests were then made to compare the performance with the different power sources. Results showed that the robot was about 40% faster with the larger cells than with the single 6V cell. The 20% weight increase for such a large increase in performance is justified using the larger batteries; so subsequent mobility tests were done with the large batteries only. Since the current load on the batteries is only about 350 mA, the CR2 batteries lasted in excess of 4 hours of operation.

The robot was controlled to run over obstacles of various heights. The largest obstacle that could successfully be overcome, without high centering and toppling of the robot, measured 3.8 cm. Traction on hard slippery surfaces was improved by the wider rubber-coated wheel-legs. The robot was also tested on a carpeted incline at various angles. When the speed of the robot was sufficiently reduced, it was able to climb inclines at angles up to 25 degrees. At higher speeds, the front wheel-legs had a tendency to lift off the surface of the incline and cause the robot to topple backwards. Video data indicates that the turning radius of the robot is about three to four body-lengths. This is a somewhat larger turning radius than for Mini-Whegs™ 5, and is most likely due to its more compact design.

B. *Mini-Whegs™ 9J*

The addition of a jumping mechanism increases the size of Mini-Whegs™ 9J to 7.6 cm by 10.4 cm, and increases the weight to 191 g. By using a similar design and materials as Mini-Whegs™ 7, the weight of the robot is kept below the weight of the original jumping prototype, Mini-Whegs™ 4J, despite the addition of steering and radio control components.

After experimenting with a number of different size and stiffness springs, a spring was selected that allows a jumping height of 15–18 cm to be achieved (Fig. 3). Since the robot uses the same drive train components as Mini-Whegs™ 7, the added weight of the jumping mechanism slows it down somewhat. The combination of independent running and jumping modes of locomotion in the same robot justifies a slight decrease in performance. By jumping, the robot is able to overcome more difficult terrain than other Mini-Whegs™.

IV. Discussion and Future Work

While Mini-Whegs™ easily overcome obstacles about 25% larger than the radius of their wheel-legs, they often high-center and topple over when faced with even larger barriers. A longer wheelbase or a third axle would reduce the chance of toppling over. However, increasing the size of the robot is not a design goal for the robot. Instead, the addition of a tail would improve balance on large obstacles. The tail would also allow the robot to climb steeper inclines without toppling.

Mini-Whegs™ 7 and Mini-Whegs™ 9J both have enclosed bodies, allowing them to perform in a wider range of environments than previous version. However, these new robots are not waterproof. A fully sealed version would increase the usefulness of the robot in outdoor conditions even further.

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