Preliminary Design and Kinematic Analysis of a Mobility Platform with Two Actuated Spoke Wheels

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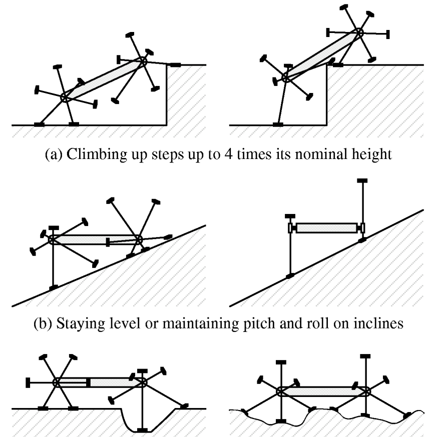
***Abstract* – IMPASS (Intelligent Mobility Platform with Active Spoke System) is a novel locomotion system concept that utilizes rimless wheels with individually actuated spokes to provide the ability to step over large obstacles like legs, adapt to uneven surfaces like tracks, yet retaining the speed and simplicity of wheels. Since it lacks the complexity of legs and has a large effective (wheel) diameter, this highly adaptive system can move over extreme terrain with ease while maintaining respectable travel speeds. This paper presents the concept, preliminary kinematic analyses and design of an IMPASS based robot with two actuated spoke wheels and an articulated tail. The actuated spoke wheel concept allows multiple modes of motion, which give it the ability to assume a stable stance using three contact points per wheel, walk with static stability with two contact points per wheel, or stride quickly using one contact point per wheel. Straight-line motion and considerations for turning are discussed for the one- and two-point contact schemes followed by the preliminary design and recommendations for future study.**

Index Terms* – *IMPASS, rimless wheel, actuated spoke wheel, mobility, locomotion.

I. INTRODUCTION

Intelligent mobility platforms which can handle extreme terrain have many important application areas: scientific exploration, environmental monitoring and protection, anti-terror response, and search-and-rescue missions are some examples where the use of such robots is a necessity [1]. In a report [2] prepared for the Office of the Secretary of Defense Joint Robotics Program on the lessons learned from the robot assisted search and rescue efforts at Ground Zero following the 9/11 World Trade Center tragedy, robot mobility is noted as the major limitation of current robotic technology and recommends that other alternative locomotion strategies which are more effective must be further investigated.

Legged vehicles can provide greater mobility than wheels or tracks by enabling discontinuous contact with the surface. In the past decade, there have been several legged vehicles developed for unstructured environment applications [3, 4]. However, the problem of legged vehicles is that they are too slow and mechanically too complex. In this paper, we present the concept, preliminary design and the kinematic analysis of a novel high-mobility locomotion platform for unmanned systems in unstructured environments which incorporates the benefits of tracked, wheeled, and legged systems. IMPASS (Intelligent Mobility Platform with Active Spoke System) is a novel locomotion system concept that utilizes rimless wheels with individually actuated spokes to provide the ability to step over large obstacles like legs, adapt to uneven surfaces like tracks, yet retaining the speed and simplicity of wheels (Fig. 1.) Since this system lacks the complexity of legs and has a large effective (wheel) diameter, this highly adaptive system can move over extreme terrain with ease while maintaining respectable travel speeds, making this novel system an excellent candidate for unstructured environment applications.


(a) Climbing up steps up to 4 times its nominal height

(b) Staying level or maintaining pitch and roll on inclines

(c) Terrain adaptation, multiple contacts with surface for stability

Fig. 1 Some examples of the mobility and terrain adaptability of IMPASS.

II. LOCOMOTION STRATEGIES FOR ROUGH TERRAIN

A. *Alternate Robot Locomotion Strategies*

Besides using wheels, tracks, or legs, there are several clever ideas currently under development for alternative robot locomotion strategies for unstructured environments. Mobile platforms that use spoked wheels or similar mechanisms include the Scout [5, 6], RHex [7], Whegs [8, 9], and the expanding wheel vehicle [10]. Scout [5] is a small cylindrical rolling robot designed to be operated over relatively even surfaces. To improve its limited mobility, one prototype of the Scout has a single degree of freedom umbrella like mechanism to increase the diameter of the wheel [6] to increase the clearance between the robot body and the ground. RHex [7] is a compliant-legged hexapod with a simple clock-driven open-loop tripod gait. RHex is different from other legged robots in the sense that its legs rotate a full circle acting as a single spoked wheel. The Wheg series of robots [8, 9] is another derivation of the spoked wheel concept utilizing compliant appendages. The Wheg II is a robot [8] with six Whegs developed from abstracted cockroach locomotion principles. The smaller version, Mini-Wheg [9], is a robot with four Whegs using an alternating diagonal gait. The expanding wheel vehicle [10] has four wheels that can expand based on polyhedral single degree-of-freedom expanding structures using prismatic joints. This adds navigational capabilities by allowing the wheels to expand according to the requirements of the terrain. Other interesting approaches to deal with highly variable, rough terrain include the JPL Sample Return Rover (SRR) [11, 12] for planetary exploration and the Shrimp rover [13]. The SRR can actively modify its kinematic configuration to improve its rough terrain mobility while the Shrimp rover uses a passive structure approach with a unique mechanism using an articulated fork and two lateral bogies with six wheels.

B. *The IMPASS Concept*

All of the mobile platforms shown above share some similar aspects with the IMPASS concept: the idea of spoked wheels, the use of compliant legs, the ability to reconfigure its structural kinematic configuration, leg-wheel hybrid locomotion, and variable diameter wheels, to name a few. However, while IMPASS shares some of the characteristics and the resulting benefits of these systems, IMPASS is fundamentally different from all of them.

The key to the concept of IMPASS is its ability to actuate individual spokes with intelligence. While current systems that use some flavor of spoked wheels have only one degree-of-freedom to change its effective diameter [6, 10] or rely on passive compliance [7, 8], the system of actively actuated spokes enables IMPASS to have extreme mobility over rough terrain. As illustrated in Fig. 1, the spokes can act as active legs to pull and push the robot body for climbing, enable the robot to change or maintain its angle (pitch and roll) relative to the ground, adapt to uneven surfaces and act as active suspensions, or increase the clearance between the body and the ground for obstacle avoidance. Fig. 2 shows a sequence of pictures illustrating the ability of an IMPASS concept with two actuated spoke wheels and an actuated tail to climb over a wall four times its nominal height.

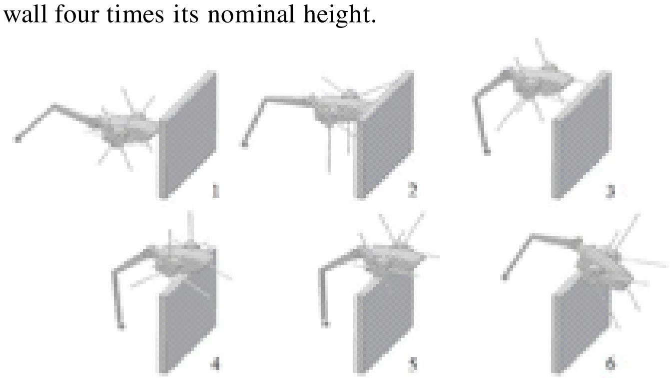


Fig. 2 A two actuated spoke wheel IMPASS climbing over a wall.

Though empirically stable, the spokes can also allow the robot to have additional contacts with the ground and to change the kinematic configuration of its structure for added stability during manipulation tasks if needed. Due to the additional actuators required for the spokes, IMPASS is more complex than RHex and Whegs based robots, but its mobility and versatility can be comparable to, or even surpass those of legged vehicles while maintaining simplicity in mechanical structure and control. Since the spokes pass through the hub of the "wheel" unit, only three actuators are required to actuate the six spokes. The ability to change its effective diameter also enables it to move faster than other spoked wheel based robots that have equal nominal diameter.

1) *Fixed stroke locomotion*: On relatively even terrain, IMPASS can operate with the stroke of each spoke fixed and move simply utilizing the compliance of their shanks like Wheg based robots, or implement gaits similar to those of RHex controlling only the rotation of each wheel unit to conserve power. Even in this mode, the motion of IMPASS would be relatively smooth since it has a large number of spokes (six spokes per wheel unit, compared to three for Whegs and only one for RHex).

2) *Simple gait motion*: If a smoother ride is needed, the three actuators can control the six spokes of each wheel unit following a simple predetermined coordinated spoke motion sequence with no terrain sensing or actively controlled adaptation, thus acting as treads moving over flat terrain. However, the real benefit of IMPASS lies in its ability to actively actuate the individual spokes with intelligence to adapt to the terrain and to use the spokes as legs for climbing over obstacles.

3) *Motion planning for optimum internal configuration:* At a certain stance of the vehicle over the terrain, IMPASS has the ability to change its internal kinematic configuration by adjusting the stroke of its spokes. Though empirically stable on even terrain, by adapting its internal configuration IMPASS can move over hills with steeper angles and increase its stability. Given the positions of the foot contact points on the ground, one task for the motion planner is to generate the optimal joint variables (stroke for the spokes and angular rotation for the wheel) for maximizing its stability, ground clearance, or traction.

4) *Active coordination of spokes for uneven terrain adaptation*: Whether the vehicle is autonomous or remotely controlled by an operator, the actuation of each individual spoke must be autonomous based on data obtained from the on-board sensors and/or the geometric terrain information. Depending on the number of foot contact points, the clearance between the ground and the body, and the constraints for internal configuration, a strategy for coordinating the motion of the spokes can be formulated based on the terrain profile geometry by modeling it as a closed kinematic chain with changing topology. If the geometry of the terrain becomes

extreme or the robot needs to climb over a large obstacle, we must use a different strategy as explained next.

5) *Motion planning of spokes for extreme terrain or for climbing*: When IMPASS needs to move over extreme terrain or encounters a large obstacle that it cannot handle with the uneven terrain adaptation method, the motion planner must use the extreme terrain method. IMPASS can theoretically climb over obstacles 4 times its nominal height (Fig. 2); however, generating the necessary motion sequences for the spokes is a challenging task. First of all, unlike legs with multi degrees-of-freedom, the wheel unit of IMPASS has very limited choices of positions for placing its feet on the ground thus each motion of the spokes must be carefully planned to maximize its ability to cope with the extreme terrain. Second, since the spokes are being used as legs, collision and interference with the obstacles and the spokes now becomes an important factor to be considered. We are currently developing algorithms to plan and coordinate the spoke motion in order to overcome the large obstacles or extreme terrain it must go over, and to do so in a stable fashion.

6) *Steering*: Skid steering, or using differential rotations of the left and right wheel units, is not desirable for spoked wheel systems since this creates bending moments on the spokes and drags the foot at the end of the spoke in contact with the surface. Utilizing its ability to change its effective diameter, preliminary analysis of the novel steering methods such as having different effective diameters on the left and the right is presented in this paper.

At this stage, the overall concept of IMPASS is not yet complete. In this paper, we present our on going research on a robot utilizing the IMPASS concept with two actuated spoke wheels and an articulated tail.

III. PRELIMINARY KINEMATIC ANALYSIS

A. *Kinematic Model and Configuration*

The development of the kinematic models for the actuated spoke wheel is based on a rimless wheel with three linearly actuated spokes that pass through the axis of the wheel in parallel planes. The angle between the spokes, β, is fixed at 60° as shown in Fig. 3. Three spokes per wheel were chosen as a balance between the requirements for acceptable mobility and the increasing mechanical complexity that comes with adding additional spokes. Having the spokes pass through the axis of the wheel allows the number of actuators for the spokes to be reduced, as only three actuators are necessary for the independent motion of the spokes. The two actuated spoke wheels considered in this analysis are driven by a single axle, so that the two actuated spoke wheels always rotate in phase. Thus not including the articulated tail with the caster wheel for the robot shown in Fig. 2, only a total of seven motors are required for the locomotion of the robot.

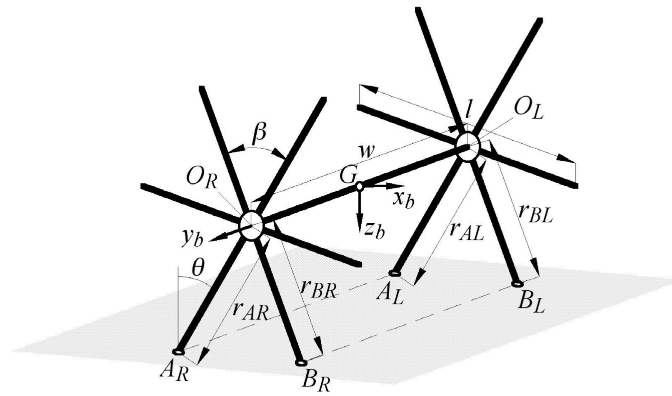


Fig. 3 Two actuated spoke wheels with a single axle.

1) *Coordinate system*

The coordinate system for the model is defined based on the SAE J670e convention in which the x-axis is defined in the direction of positive travel, and the z-axis is oriented such that forces from the spokes to the ground are positive, as shown in Fig. 3. The robot configuration consists of a robot that has two actuated spoke wheels, spaced apart of a width of w, and point G at the center of the axle. Since the actuated spoke wheels considered here are driven by a solid axle, they are always in phase ($\theta_R = \theta_L = \theta$).

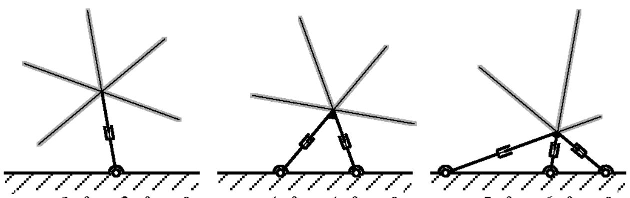
The ground is represented by the inertially fixed reference frame $N\{x_N, y_N, z_N\}$. The robot travels along a path frame, $P\{x_P, y_P, z_P\}$, that is rotated from the N-frame by a yaw angle ϕ about the z_N axis. A body fixed frame, $B\{x_b, y_b, z_b\}$, is created by choosing different left and right side spoke lengths, which will cause the robot to roll through an angle ψ about the x_P axis. Finally, a wheel fixed frame, $W\{x_w, y_w, z_w\}$, is created by the actuated spoke wheel pitching through an angle, θ, relative to the body about the y_b axis.

2) *Degrees of freedom*

The preliminary analyses presented here will consider motion over flat terrain only and the articulated tail with the caster wheel will not be included in the analysis. Since each of the three spokes in a wheel can be independently actuated, it becomes clear that it would be possible for the actuated spoke wheel to have one, two, or three contact points with the ground, with each of these modes of locomotion having different mobility characteristics. With the assumption of an imposed no-slip condition at each contact point with the ground, this contact point is modelled as a revolute joint between the ground and the actuated spoke wheel. Equation (1) gives Grubler's equation [14] to calculate the planar mobility of a single actuated spoke wheel in different modes.

$$M = 3(n-1) - 2f_1 - f_2 \tag{1}$$

Where M is the mobility, n is the number of links, f_1 is the number of 1 degree of freedom (DOF) joints, and f_2 is the number of 2 DOF joints. As shown in the kinematic diagram in Fig. 4 (a), an actuated spoke wheel with a single contact point with the ground has two degrees of freedom, as the angle and length of the spoke in contact with the ground can be independently controlled. For the two-point contact case, the degrees of freedom for a single actuated spoke wheel is one, and for the three-point contact case, the degrees of freedom for a single actuated spoke wheel is zero, as shown in Fig.s 4 (b) and (c) respectively. This will give each mode a different mobility characteristic and will require different strategies for motion as will be presented next. Note that as the actuated spoke wheel advances, the spokes will make and break contact with the ground changing the topology of the mechanism.



$n = 3, f_1 = 2, f_2 = 0$, $M = 2$ — (a) One point contact
$n = 4, f_1 = 4, f_2 = 0$, $M = 1$ — (b) Two point contact
$n = 5, f_1 = 6, f_2 = 0$, $M = 0$ — (c) Three point contact

Fig. 4 Kinematic diagram of a single actuated spoke wheel and its degrees of freedom for different modes.

B. *Straight Line Motion*

1) *One-Point Contact Mode*

The kinematic velocity equations are derived by finding the velocity of point *G* relative to a fixed point in the *N*-frame. Choosing the ground contact of the right wheel, A_R as the fixed point in the inertial frame, the position of point *G* is then

$$\vec{r}_{G/A_R} = -r_{A_R}\vec{z}_w - w/2\vec{y}_b \quad (2)$$

and taking the time derivative of this position vector gives the equations for the velocity of the center of the axle. Recognizing that the pitch angle, ψ, is a function of the leg lengths r_{AR} and r_{AL} through the relationship

$$\psi = \sin^{-1}\left(\frac{r_{AL} - r_{AR}}{w}\right) \quad (3)$$

allows one to substitute to remove ψ from these velocity equations. The constraints caused by the no-slip conditions at the two ground contact points (one for each wheel) ensure that the left and right side spokes in contact with the ground actuate at the same rate and that the velocity of the robot is constrained to the current heading angle. These constraints limit the motion of the actuated spoke wheel to a plane over the course of a step. A set of differential kinematic equations can be derived using the three equations that result from taking the time derivative of (2) and the equations that result from the constraints above [15]. The resulting complete kinematic differential equations are too long to list here, but interested readers are encouraged to contact the authors for more information. In summary, there are seven states given by the three translational velocities of point *G*, $\dot{x}$, $\dot{y}$, and $\dot{z}$, two linear velocities of the legs, $\dot{r}_{AL}$ and $\dot{r}_{AR}$, and two rotational velocities given by the change in heading angle, ϕ, and the change of the wheel angle $\dot{\theta}$. From the mobility analysis, the constraint equations are given as

$$\dot{\phi} = 0 \quad (4)$$

$$\dot{r}_{AR} = \dot{r}_{AL} \quad (5)$$

Using a vertical speed u_z and a longitudinal speed u_x to specify the motion along the current heading angle, the resulting input equations are

$$\dot{z} = u_z \quad (6)$$

$$\dot{x} = u_x \cos\phi \quad (7)$$

These equations allow the motion of the robot to be determined for a given set of input speeds u_z and u_x. This arbitrary nature of the result highlights the flexibility of the locomotion of the actuated spoke wheel.

Since it is possible to independently actuate the spokes used for the current step and those to be used in the next step, it is possible to select the wheel angle at which the robot will switch contact points. The optimal angle at which to switch contact points is 30° since the required rotational velocity of the axle needs to be discontinuous from one step to the next for all switching angles other than 30°. This represents the instant during the step at which switching would occur when the legs form an isosceles triangle. Using this switching angle, choosing a height at which to keep the robot will enforce a step length. The robot in this configuration would be able to maintain a constant height of any positive value up to $\sqrt{3}l/2$, at which point the legs are fully extended and the robot would be taking a step of length *l*.

Moving at a constant height is a beneficial motion scheme since energy is not wasted by raising and lowering the center of mass, but this is only one of many motions possible by the one-point contact mode, as the inputs u_z and u_x are arbitrary. The ability of the robot to adjust its height, and thereby adjust its step length, allows it to move in a manner best suited to fit the situation. This analysis could be reproduced for other motion schemes better suited to other tasks.

2) *Two-Point and Three-Point Contact Mode*

In the two-point contact mode, with a no-slip condition at both contact points for each wheel, the distance between the two contacts is fixed. Since the angle between the spokes in contact with the ground is constant (β), it is possible to express the position of the axle of the robot as a function of the wheel angle, θ, using the law of sines. It can be shown that the relationships for the length from the rear contact point *A* to the axle, r_A, and for the length from the forward contact point *B* to the axle, r_B, are given by

$$r_A = t\frac{\sin(\pi/2 + \theta - \beta)}{\sin\beta} \quad (8)$$

$$r_B = t\frac{\sin(\pi/2 - \theta)}{\sin\beta} \quad (9)$$

where t is the ratio of the step distance $\overline{AB}$, to the total length of the spoke l. The flexibility of the design allows for t to be chosen from for any positive value up to $\sqrt{3}/2$, at which point the spoke is fully extended during the step. Once a step length is chosen, the robot will move along a specified path as a function of the wheel angle. The prominent feature of this motion is the repeated arcing pattern of the axle's path. This is analogous to the motion of the center of gravity of a passive rimless wheel, which is often used to approximate bipedal human walking [16]. While the motion of the actuated spoke wheel is not constrained to a circular arc as for the case of the passive rimless wheel, it does provide a viable scheme for statically stable walking with as few as two actuated spoke wheels.

As the mobility analysis of the three-point contact mode shows zero degrees of freedom (Fig. 4 (c)), the three-point contact mode is not a scheme for motion. However, the three-point contact scheme is still of use since this will allow the robot to take a very wide stance on terrain for improved stability. This statically stable position can be used for bracing at rest which could be useful for the robot performing tasks such as digging, drilling, or other manipulation tasks. This stable position itself is not unique since the spokes of the left and right wheels can be adjusted independently to brace the robot in a stance best suited for the terrain.

C. Turning Motion

Instead of turning by differential steering as is common in robots with two traditional wheels, or Ackerman steering as found in automobiles, turning for the two actuated spoke wheel robot can be implemented by actuating the spokes to have different spoke lengths between the left and right, changing the effective radii of the two wheels independently.

The robot in the one-point contact mode pivots about an axis in the z_N direction at the intersection of the two lines connecting the left and right ground contact points as shown in Fig. 5. When the robot takes steps of equal lengths, these pivot lines are always parallel, but by making one side's step longer than the other, the direction of this line is changed for the next step. This changes the heading angle, turning the robot in a discrete fashion in an amount related to the difference in step lengths, as shown in Fig. 5.

Each step taken with unequal lengths introduces a change in the heading angle, denoted by $\Delta\phi$. This relationship is given by

$$\Delta\phi_i = \tan^{-1}\left(\frac{t_{Li} - t_{Ri}}{w}\right) + \tan^{-1}\left(\frac{t_{Li-1} - t_{Ri-1}}{w}\right) \qquad (10)$$

where t_R and t_L are the step lengths of the right and left actuated spoke wheels, respectively.

In the two-point contact mode, a similar approach of taking steps of different lengths with the left and right wheels may be applied for turning. However, this cannot occur without slipping at some of the ground contact points. Skidding conditions have not been considered at this time, but are listed in the conclusion as a topic for future study. Introducing compliance in the spokes is one way of making turning in the two-point contact mode possible without skidding.

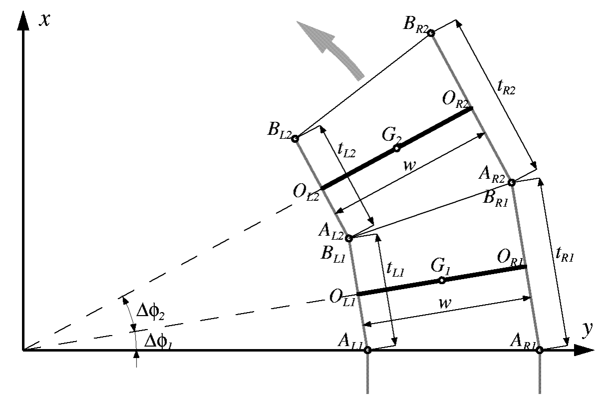


Fig. 5 Discrete turning by changing the spokes length for the one-point contact mode.

IV. PRELIMINARY DESIGN

To evaluate the models and methods developed, and to provide a test bed for future research, an IMPASS concept demonstrator with two actuated spoke wheels is being built at Virginia Tech's Robotics and Mechanisms laboratory. For this prototype, we are developing a small, light-class unit under 50 Kg with a spoke length of 60 Cm and a body width of 66 Cm.

A. Actuation and Mechanism

The designing of the active spoke system is an interesting and challenging task in and of itself. To minimize the number of actuators in a single wheel unit and to maximize the stroke of the spokes, each of the six spokes passes through the hub of the wheel unit; thus there are actually only three spokes and only three actuators are required. Fig. 6 shows the design of a two actuated wheel and an articulated tail IMPASS robot under development. The spokes are actuated using gear head DC motors (Fig. 7 (a)) with a simple rack and gear mechanism to convert the rotational motion of the motor output to the linear motion of the stroke. The spokes consist of a center rack section which engages with the driving mechanism, a shank section which has compliance to act as passive suspension and for safety, and a foot connected to the shank with a compliant ankle joint to increase the contact area and for a better foothold and to absorb the shock.

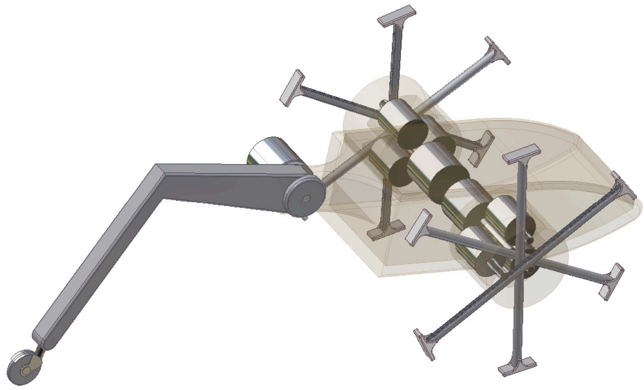


Fig. 6 IMPASS with two actuated spoke wheels and an articulated tail.

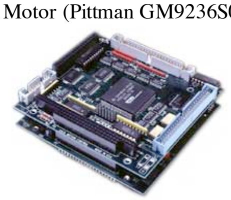
Since the wheel unit needs to be rotated in full, rotating electrical connectors such as slip ring assemblies with a "through-shaft" configuration is used for connecting power and for data communication between the wheel-axle unit and the main body of the robot.

B. *Sensing*

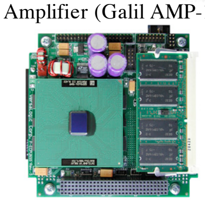
The terrain profile information is usually obtained by on-board sensors such as laser rangefinders or stereovision cameras. For Virginia Tech's DARPA Grand Challenge vehicle, we use a pair of Sick Optic laser rangefinders with two Eaton VORAD radar units fused together to create a local terrain map. We may implement these types of sensors with IMPASS in the future; however, the first prototype is being equipped with load cells and simple contact sensors at the tip of each foot to be tested under controlled environments with known terrain geometry. We are currently developing methods to generate motion sequences of the spokes to adapt to the changing terrain without the geometric terrain information by relying only on simple contact force sensors at the feet to determine the basic geometric information of the ground in contact (height and surface normal direction) for terrain with variation less than the nominal radius of the wheel unit. Other sensors may be added to the spokes to measure the bending of the shank to detect collisions of the spokes with obstacles.

(a) Motor (Pittman GM9236S025)

(b) Amplifier (Galil AMP-1940)



(c) Controller (Galil DCM-1280)



(d) PC/104 CPU (VersaLogic Jaguar)

Fig. 6 Electronic components.

C. *Control*

The motor control is done by a PC/104 bus 8-axis motion controller (Fig. 6 (c)) connected to a PC/104 single board computer (Fig. 6 (d)) with a 850 MHz Pentium III CPU running LabView. Nickel-Metal Hydride battery packs provide power to the DC motors through two, four channel servo amplifiers with 7 amps continuous, 10 amps peak capacity. The robot with onboard USB vision cameras will initially be remote controlled via a wireless 802.11b connection to a laptop computer.

V. Conclusion

In this paper, a novel locomotion system concept that utilizes rimless wheels with individually actuated spokes to provide the ability to step over large obstacles like legs, adapt to uneven surfaces like tracks, yet retaining the speed and simplicity of wheels is presented. A robot using two actuated spoke wheels is analyzed on flat terrain using a one-, two-, and three-point contact per wheel scheme. These modes are analyzed to show the possible motions when constrained to non-slipping contacts with the ground. It is shown that the one-point contact mode has two degrees of freedom where the output motion can be arbitrarily selected. This mode would allow for moving while maintaining a constant height, which is analyzed here. The two-point contact mode is shown to have one degree of freedom, and that by choosing a step length, the path of the wheel is determined as a function of the wheel angle. This mode of locomotion allows for statically stable walking with only two wheels, and could be used for carrying heavy payloads. The three-point contact scheme is shown to have zero degrees of freedom, but would allow for additional stability during stationary tasks by letting the robot assume a wide stance with multiple contacts. Turning for the system occurs discretely by changing the heading angle for every step by taking steps with different spoke lengths for the right and left wheels.

Future work will focus on expanding the understanding of how the actuated spoke wheel can be used to provide improved mobility. Further kinematic analysis needs to be performed to understand the general three dimensional motion of the robot as it transitions from one motion scheme to another, to study the motion over uneven terrain, and to determine the functionality of the actuated spoke wheel robot in other configurations, such as allowing the left and right wheels to rotate independently. Work will continue into developing algorithms and strategies for intelligent motion planning and coordination of the active spokes. Other work will include dynamic analysis, a study of energetics of the various actuated spoke wheel configurations, and completing the prototype for experimentations.

Acknowledgment

This material is based upon work supported by the National Science Foundation under Grant No. 0535012. The authors would also like to thank Virginia Tech’s Office of the

Provost, the Office of the Vice Provost for Research, and the university's Central Capital Account for funding this research through the ASPIRES award.

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