Proceedings of the ASME 2009 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference
IDETC/CIE 2009
August 30 - September 2, 2009, San Diego, California, USA

DETC2009-86925

CONSIDERATIONS FOR MOTION PLANNING OF A ROBOT WITH TWO ACTUATED SPOKE WHEELS IN THE TWO-DIMENSIONAL SAGITTAL PLANE: GAITS AND TRANSITIONS

Shawn C. Kimmel
RoMeLa (Robotics and Mechanisms Lab)
Department of Mechanical Engineering
Virginia Tech
Blacksburg, Virginia 24061
Email: skimmel@vt.edu

Dennis W. Hong*
RoMeLa (Robotics and Mechanisms Lab)
Department of Mechanical Engineering
Virginia Tech
Blacksburg, Virginia 24061
Email: dhong@vt.edu

ABSTRACT

IMPASS (Intelligent Mobility Platform with Active Spoke System) is a novel mobile robot which is driven by a pair of rimless spoke wheels which can alter the length of any given spoke in the hub. A highly mobile robot such as IMPASS could prove very valuable in applications where the terrain is complex and dangerous, but for this platform to be practical for real world use, motion control of the actuated rimless wheel must be automated. This work discusses considerations for motion planning concerning the transitions from step to step in the two-dimensional sagittal plane. Each step transition can be defined by a switching angle, which is the angle made between the back spoke and a reference axis. Presented is a review of the types of step transitions that are advantageous for ascending and descending obstacles, as well as traversing terrain with minor irregularities. These step transitions have been tested in simulation and on a physical prototype, the results of which will be discussed.

INTRODUCTION

In the last decade, there has been a significant increase in the use of robots in real world applications. This usage will only increase in years to come, most likely at an accelerated rate. As the demand for robotic solutions expands, so will demands on the physical abilities of robots. Currently one of the biggest weaknesses in robotic technology is mobility. Wheeled robots tend to be simple and efficient, but are often limited to relatively smooth terrain. Legged robots on the other hand are better equipped to deal with irregular terrain. Unfortunately, legged robots are inherently more complex, often resulting in slow and inefficient operation.

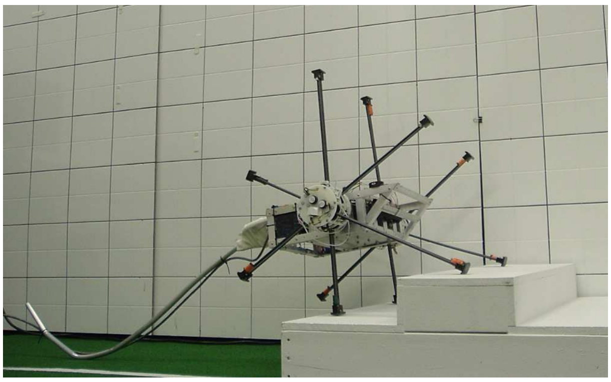


Figure 1. A PROTOTYPE OF THE IMPASS ACTUATED SPOKE WHEEL PLATFORM HAS BEEN DEVELOPED FOR MOTION PLANNING RESEARCH.

Developing a highly mobile platform that is practical for real world applications has proven difficult. To achieve both mobil-

*Address all correspondence to this author.

ity and simplicity, “leg-wheel” robots have been developed that include both the leg and wheel concept into a single mechanism. These mechanisms tend to be simpler than legged platforms, but far more mobile than wheeled platforms.

The platform proposed in this paper is IMPASS (Intelligent Mobility Platform with Active Spoke System), a highly mobile leg-wheel hybrid. This robotic platform is based around a rimless spoke wheel with individually actuated spokes. The spokes have the ability to increase or decrease their length during operation. A prototype has been developed which includes two actuated rimless wheels that rotate about a common axis and a body with a trailing tail that provides the reaction force for rotation of the wheels. This prototype, shown in Figure 1, was used for experimenting with the ideas set forth in this paper.

Leg-wheel hybrid robots have been developed to improve upon the mobility of wheeled robots. By having the capability to traverse the ground with discontinuous contact points, the robots are able to overcome otherwise non-traversable segments of the terrain. Crossing complex terrain requires special consideration for the motion of the robot. There are a couple of robots similar to IMPASS that can provide some insight into motion planning considerations.

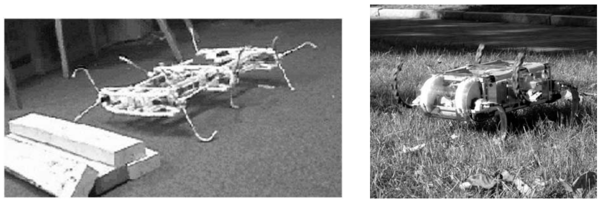
The Whegs robot, shown in Figure 2(a), was developed at Case Western University, and is a three axel leg-wheel hybrid. This robot uses a biologically inspired alternating tripedal gait similar to that of a cockroach [1]. The robot can traverse obstacles of up to 1.5 times the spoke length [2]. This is done passively with a compliant drive shaft. The front spokes are normally out of phase, but align during a climb due to the high torque.

RHex is a highly mobile robotic platform which also uses a design with six rimless wheels. The robot, shown in Figure 2(b), has a few different locomotion schemes. For general unstructured terrain, an alternating tripedal gait can be used, similar to that of the Whegs robot. However, in a stair climbing situation, a back to front wave gait can be used to improve the mobility of the robot [3]. The phase of the wave gait is the key feature that determines its effectiveness. Using an optimized gait, the robot is capable of climbing a set of 0.2 meter steps.

As will be shown, there are multiple ways to control the gaits for IMPASS. Factors that determine the quality of a step are both the geometry of the robot and the physical characteristics of the hardware. The transitions set forth in this paper were tested in simulation and effectively used to control the current IMPASS prototype. Testing has indicated where there is room for improvement, and has provided insight into good avenues of future research to pursue. These will all be discussed in this paper.

GAITS OF IMPASS

IMPASS is a high degree of freedom (DOF) system that can contact the ground in many different configurations. A single rimless wheel with six spokes can contact the ground in three different ways, shown in Figure 3. By making the assumption that the contact points cannot slip, they can be modeled as revolute joints. The legs are modeled as prismatic joints. The DOF for each configuration relative to the ground, M, can be calculated using Grublers equation, given by



(a) WHEGS ROBOT [2]. (b) RHEX ROBOT [4]

Figure 2. LEG-WHEEL HYBRID DESIGNS SIMILAR TO IMPASS.

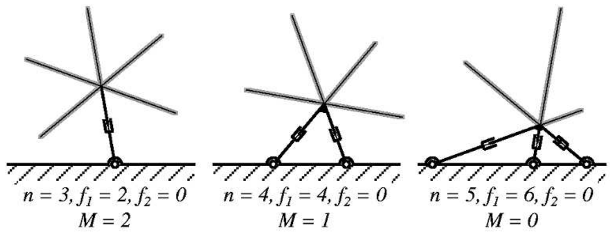


Figure 3. A SINGLE ACTUATED RIMLESS WHEEL CAN CONTACT THE GROUND IN THREE WAYS, RESULTING IN TWO, ONE, OR ZERO DEGREES OF FREEDOM [5].

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

where n is the number of links,which can be taken as 3,4 or 5 as indicated in Figure 3, f_1 is the number of one DOF joints, and f_2 is the number of two DOF joints. From this equation, it can be determined that the one-point contact case has two DOF [5, 6]. This can be visualized by the hub rotating about the contact point while the spoke changes length. The two-point contact case has a single DOF, the motion of which will be discussed in a later section. Finally, the three-point contact case has zero DOF.

Two of the configurations possess more than zero degrees of freedom and can be used by the robot to traverse terrain. There are two gaits for the robot which are defined by these configurations, the one-point contact gait and the two-point contact gait. Each gait is unique in its mobility characteristics, which results in unique advantages and disadvantages for terrain traversal. This paper specifically investigates the path flexibility and static stability of the gaits.

Path flexibility is described as the robot’s control over the trajectory of a point on the body. The static stability of the robot is determined by two factors, the center of gravity (CG) location

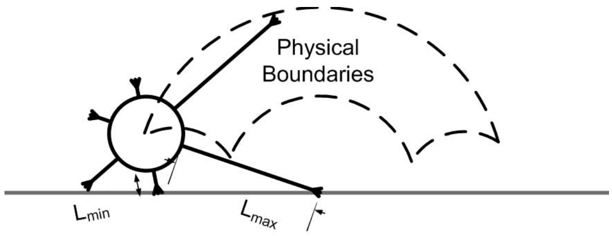


Figure 4. THE PHYSICAL BOUNDARIES OF THE HUB CENTER ARE SHOWN FOR THE ONE-POINT CONTACT GAIT, DETERMINED BY THE MINIMUM AND MAXIMUM SPOKE LENGTHS, L_{min} and L_{max}.

and the support polygon. The CG of the robot can be described by (x_{CG}, z_{CG}). The support polygon is the outline that is formed by the the contact points. For the two-dimensional sagittal plane, this support polygon will be one dimensional, including the tail and the front most spoke contact point. As long as the vertical projection of the CG, x_{CG}, is located within the support polygon, the robot is considered stable.

One-Point Contact Gait

The one-point contact gait for IMPASS exhibits excellent mobility. This gait can be used to position the hub anywhere in the two dimensional sagittal plane within the robot's physical limitations. This is shown in Figure 4. The tradeoff for this flexibility is stability. The support polygon for the robot is reduced in this gait with only one spoke from each wheel contacting the ground, forcing more emphasis on the placement of the CG.

The physical constraints are the minimum and maximum spoke lengths, L_{min} and L_{max} respectively. For the current prototype, these values are 3.5 inches and 19 inches. The large solution space of the one-point contact case provides infinite ways to leave one step and enter the next. This is a great advantage to motion planning because it provides the flexibility to focus on certain goals. The methods and considerations for one-point contact step transitions will be discussed in a later section.

Two-Point Contact Gait

On terrain that is more unstable, the two-point contact gait is preferable. In this situation the robot will have five points of contact (two feet from each wheel and the tail) resulting in a larger support polygon. The downside is that the kinematics of this gait constrain the motion to one DOF. Motion planning therefore becomes much less flexible.

The path of the hub center in the two-point contact gait can be described as a circle. This circle is described by a center point (x_c, z_c) with radius r_c based on the contact points (x_1, z_1) and (x_2, z_2). The properties of the circle can be calculated by the equations

$$x_c = x_1 + \frac{|\vec{d_g}|}{\sqrt{3}} \cos(30^\circ + \alpha_g) \tag{2}$$

$$z_c = z_1 + \frac{|\vec{d_g}|}{\sqrt{3}} \sin(30^\circ + \alpha_g) \tag{3}$$

$$r_c = \frac{|\vec{d_g}|}{\sqrt{3}} \tag{4}$$

where (x_1, z_1) is the back spoke contact point, $\vec{d_g}$ is the vector that connects the back spoke contact point to the front spoke contact point, and α_g is the pitch of vector $\vec{d_g}$. The two values $\vec{d_g}$ and α_g are shown in Figure 7 and defined by the equations

$$\vec{d_g} = \sqrt{(x_2 - x_1)^2 + (z_2 - z_1)^2} \tag{5}$$

$$\alpha_g = \arctan(\frac{z_2 - z_1}{x_2 - x_1}) \tag{6}$$

The hub center path for three consecutive steps is shown in Figure 5. The hub center trajectory for two adjacent steps will intersect in exactly two points, and it is at one of these two points which the robot must transition to the new step. One intersection is at the common contact point. This intersection would require one of the spokes to have a length of zero, so it is not feasible. The other intersection has non-zero leg lengths, but could still be outside of the physical boundaries of the robot.

The physical boundaries for the two-point contact gait are presented in Figure 6. In this graph, the x-axis is the back spoke length and the y-axis is the front spoke length. The curve plots the spoke lengths against each other as the robot rotates through a step of a given step distance. The dotted square in this graph is the physical limitations of the spoke, i.e. the minimum and maximum spoke lengths. For the step length of 17 inches shown in the graph, the robot cannot rotate continuously through the step. Therefore, a 17 inch step is not a good one to take. Given an minimum spoke length of 3.5 inches and a maximum spoke length of 19 inches, the maximum step length which IMPASS could rotate continuously through is 16.45 inches. Any step shorter than

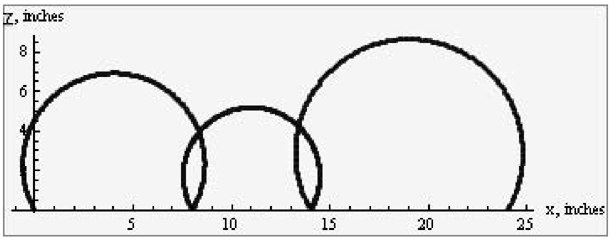


Figure 5. THE HUB CENTER PATHS FOR THREE CONSECUTIVE STEPS WITH CONTACT POINTS AT 0, 8, 14 AND 24. THE POINTS OF INTERSECTION OF THE ARCS ARE WHERE STEP TRANSITIONS CAN OCCUR.

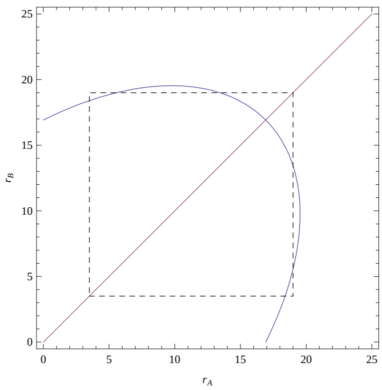


Figure 6. THIS GRAPH PLOTS THE LENGTH OF THE BACK SPOKE AGAINST THE LENGTH OF THE FRONT SPOKE DURING A STEP OF 17 INCHES. A DASHED BOX HAS BEEN INCLUDED WHICH SHOWS THE MAXIMUM AND MINIMUM SPOKE LENGTHS [7].

16.45 inches is continuous, but the range of motion is diminished with the step length.

The two-point contact gait has no flexibility within a step to change the trajectory of the robot. However, when making a transition from one step to the next, IMPASS has the flexibility to choose the trajectory for the next step by choosing the next contact point. It is important to choose a step which is continuous for the desired range of motion and allows for future steps to have continuous rotation.

ONE-POINT CONTACT TRANSITIONS

Any stable one-point contact transition requires that two feet contact the ground from each hub. Therefore, the robot must obey the kinematics of the two-point contact case at the instant of the transition. The two-point contact case has one DOF, which constrains the position of the hub center to a range of motion that forms a circle.

It is required that IMPASS must assume a hub center position somewhere on the two-point contact circle for a transition.

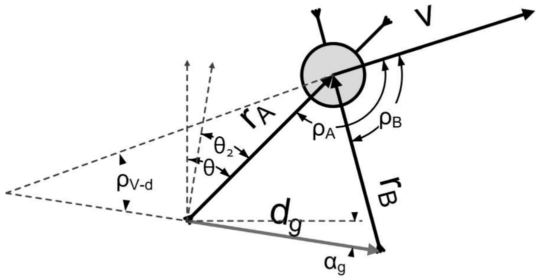


Figure 7. IMPASS SHOWN IN THE TWO-POINT CONTACT CONFIGURATION. TRANSITIONS FOR THE ONE-POINT CONTACT GAIT ARE DESCRIBED USING THE SWITCHING ANGLES, θ AND θ_2.

A given transition can be described by one of two switching angles, θ or θ_2, both shown in Figure 7. θ is the angle that the back spoke makes relative to the z axis, which is parallel to the direction of gravity. θ_2 describes the angle that the back spoke makes with the line that is normal to the ground link, $vecd_g$.

There are five transitions that will be discussed: Constant Angular Velocity, Equivalent Spoke Length, Descending Transition, Ascending Transition, and Default Transition. Each transition has distinct advantages and disadvantages associated with it.

Constant Angular Velocity Transition

One of the most important considerations in motion planning is providing a continuous motion profile to the actuators. For the one-point contact transitions, the spokes are not much of a consideration since they are either coming into contact with the ground or leaving the ground. However, the rotation of the hub must be considered since it describes motion of both previous and future steps simultaneously.

At the instant before transition, the hub's angular velocity, $\vec{\omega}_A$ is described by

$$\vec{\omega}_A = \frac{|\vec{v}_A| Sin\rho_A}{|\vec{r}_A|} \tag{7}$$

where $\vec{r}_A$ is the vector describing the rear spoke, $\vec{v}_A$ is the hub velocity, and ρ_A is the angle between the spoke and velocity vectors. These variables are shown in Figure 7. At the instant after transition, the hub's angular velocity is a function of the new contact spoke, $\vec{r}_B$, the velocity for that spoke, $\vec{v}_B$, and the relative angle ρ_B.

In a previous paper, Laney discusses the constant ω case for purely horizontal velocity on a horizontal terrain. His paper showed that the switching angle that gives a constant ω is always 30 degrees [5], where the switching angle is defined as θ.

In reality the terrain IMPASS will be traversing will not be horizontal. Also there will be a vertical component to the velocity as the robot adjusts to the terrain. The results from Laney's paper can be generalized to give the following property: if $\vec{d}_g \| \vec{v}$, then constant ω occurs at $\theta = 30^\circ - \alpha$. Vectors $\vec{d}_g$ and $\vec{v}$ can be chosen in motion planning such that they are parallel. Using this property provides the path planner with a simple correlation between the velocity and contact point vectors. However, this transition method lacks the flexibility to individually choose velocity and contact point vectors.

In decoupling the velocity and contact point vectors, a couple of assumptions are made. To prevent any significant jerk on the robot, an instantaneous change in the velocity vector will not be allowed. Therefore, $\vec{v_A}$ and $\vec{v_B}$ are set equal. Additionally, the vectors $\vec{r_A}$ and $\vec{r_B}$ are kinematically linked by the two-point contact arrangement. This linkage provides us with the relation that ρ_A is 60° greater than ρ_B. Here a new angle ρ_{v-d} is introduced in Figure 7 which describes the difference in slope between $\vec{d}_g$ and $\vec{v}$. Angles ρ_A and ρ_B can be written in terms of ρ_{v-d} and the switching angle θ shown by

$$\rho_A = \rho_{v-d} + \theta + 90^\circ, \rho_B = \rho_{v-d} + \theta + 30^\circ \tag{8}$$

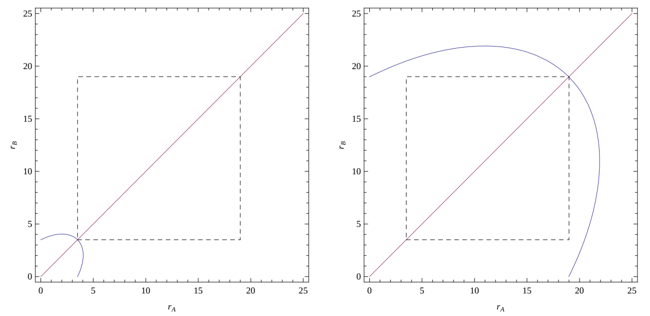
Using the assumptions above, we arrive at the equation that describes the constant angular velocity case

$$0 = \frac{|\vec{r_A}|}{|\vec{r_B}|} - \frac{Sin(\rho_{v-d} + \theta + 90^\circ)}{Sin(\rho_{v-d} + \theta + 30^\circ)} \tag{9}$$

The constant ω approach to solving one-point contact transitions is attractive because it provides a second-order continuous motion function for the hub motors. Additionally, by setting $\vec{v_A}$ and $\vec{v_B}$ equal, we are preventing the robot from experiencing any significant shock during transition. This method is beneficial for the motors, but has shortcomings in the types of terrain it can handle. The next section will discuss transitions that have more advanced mobility capabilities.

Equivalent Spoke Length Transition, $\theta_2 = 30^\circ$

The most versatile switching angle for IMPASS is $\theta_2 = 30^\circ$. In this configuration IMPASS is capable of making the largest and smallest steps across flat terrain. This is graphically shown in Figure 8. The point on the curve that corresponds to $\theta_2 = 30^\circ$ is always located on the line of unity slope that goes through $(0,0)$. As long as the maximum and minimum spoke lengths are universal for all spokes on the hub (i.e. the solution space is a square), the line of unity slope will go through the bottom left and top right corners of the constraint region. The Figure 8



(a) Minimum Step Distance (b) Maximum Step Distance

Figure 8. THE SPOKE LENGTHS, $\vec{r_A}$ and $\vec{r_B}$, ARE PLOTTED AGAINST EACH OTHER FOR THE MINIMUM AND MAXIMUM STEP LENGTHS [7].

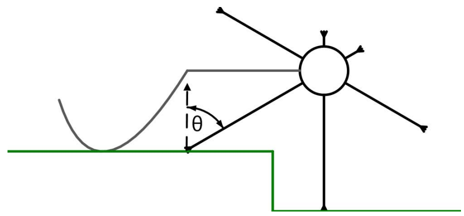


Figure 9. IMPASS DESCENDING AN OBSTACLE WITH $\theta = 60^\circ$.

shows that maximum and minimum step length occur in these corners.

With this switching angle, IMPASS is exactly halfway between the minimum and maximum switching angle. The stability is dependent on the ground link angle α, and therefore will vary from step to step. As α becomes more negative or the step distance $|\vec{d}_g|$ becomes larger, this transition becomes less stable. Additionally the stability depends on the terrain previous to the current step. For example, the robot would be much less stable if the front of the robot had just descended a negative obstacle and the tail was still on the obstacle.

Descending Transition, $\theta = 60^\circ$

The switching angle for a step determines the orientation of the contact spokes during the transition. When θ equals 30°, the back and front spoke have the same vertical displacement per unit length. As the switching angle is increased greater than 30°, the forward spoke is able to achieve a greater vertical displacement than the back spoke. This concept is presented in Figure 9, which shows IMPASS with $\theta = 60$ with equal lengths for the front and back spokes. The front spoke is clearly able to achieve a greater vertical displacement.

The aforementioned bias in vertical displacement facilitates easier transitions to terrain that is below the height of the current contact point, i.e. negative obstacles. Here, a metric is introduced

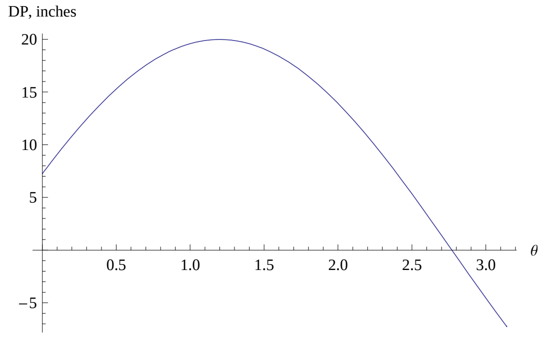


Figure 10. THE DESCENDING POTENTIAL (DP) IS SHOWN FOR EQUAL LENGTHS OF THE FRONT AND BACK SPOKES. THE MAXIMUM DP IS REACHED AT $\theta = \frac{2*\pi}{3} = 120°$.

called 'Descending Potential' or DP, which describes the ability of the robot to traverse negative terrain features. This metric is calculated by the equation

$$DP(\theta) = |\vec{r_{Bz}}| - |\vec{r_A}z| = |\vec{r_B}| \cdot \mathrm{Cos}\left[\frac{\pi}{3} - \theta\right] - |\vec{r_A}| \cdot \mathrm{Cos}[\theta] \quad (10)$$

The first term gives the vertical rise of the front spoke, and the second term gives the rise of the back spoke. According to this metric the switching angle with the greatest DP is achieved when both spokes are at maximum length and the ground link is vertical, such that $\theta = 120°$ and $\alpha = -90°$. The DP metric for this configuration is shown in Figure 10.

Implementation of this maximum DP case would lead to a precarious configuration. With both spokes at maximum length and $\theta = 120°$, the hub center will be in front of the contact points by $\frac{\sqrt{3}}{2}$ times the spoke length. Placement of the CG would need to be extremely far back to ensure a stable stance. In addition to CG issues, this configuration does not contact the bottom of the back foot. The back foot is essentially used as a hook to hold onto the top of the obstacle. The safety of the robot becomes a concern here. If the back foot slips before the front foot can contact, the robot could roll off the obstacle potentially damaging components or falling onto its back or side becoming immobilized.

This maximum DP configuration is possible, but not very practical. To find a more practical descending transition, θ is constrained to less than 90° so that the contact spoke will have normal contact with the ground. Additionally, the back spoke length is fixed at its minimum length. This helps with stability since the furthest that the hub center can overhang the obstacle is the minimum spoke length. The front spoke is fixed at its maximum value to maximize the DP.

The DP for the proposed configuration is shown in Figure 11. The robot is capable of a step height of 20 inches with

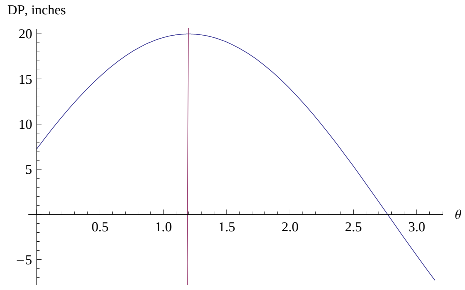


Figure 11. THE DP IS SHOWN FOR WHEN THE BACK SPOKE IS AT l_{min} AND THE FRONT SPOKE IS AT l_{max}, AND REACHES THE MAXIMUM DP AT $\theta = \frac{2*\pi}{3} = 120°$.

$\theta = 68.3°$. Again, the resulting orientation of the robot is with $vecd_g$ vertical, meaning $\alpha = -90°$. Using an α of $-90°$ gives the greatest DP, but it is not very practical. A vertical contact point vector requires the back spoke to be precariously perched at the edge. This configuration also requires the back spoke to be stuck in the bottom corner of the obstacle, which can only happen with a perfectly vertical obstacle. To address these issues, the back spoke must be moved away from the edge and the front spoke moved forward.

A switching angle of $\theta = 60°$ becomes an attractive option that moves the contact points away from the edges. Setting θ to 60° allows the front spoke to be vertical, which minimizes the compliance in the spokes. The spoke will flex minimally in the vertical orientation, providing the most reliable spoke length. This switching angle suffers a DP loss of only 0.25 inches compared to the maximum DP of $\theta = 68.3°$, while gaining a comfortable horizontal distance of 2.5 inches between the contact points. The horizontal distance can be split into 1.25 inches of clearance from the obstacle for both contact points.

If the robot needs to descend a height of less than 19.75 inches, it would be better to increase the rear spoke length than change the angle. This will give the hub more ground clearance and decrease the change in angular velocity between the two steps. Maintaining the 60° switching angle provides consistency and keeps the front spoke vertical, which are both beneficial.

Ascending Transition, Adjacent and Non-Adjacent Spokes, $\theta = 0°$

Ascending an obstacle has many geometric similarities to the descending case, but is fundamentally different in that there is less focus on stability and more on torque. The constraint from the descending case that the spokes must contact the ground on the bottom of the foot is removed for the ascending case. The robot is allowed to use the front spoke as a "hook" to pull itself onto the obstacle. This opens up the possibility of using non-adjacent spokes to climb. This gives two transitions, the Adjacent Ascending Transition and the Non-Adjacent Ascending Transition. Adjacent spokes are defined as two spokes that are separated by angle β around the hub. By using non-adjacent spokes, much larger obstacles can be climbed.

The first case investigated was transitioning over an obstacle using the bottom of the front spoke. Here we can draw lessons from the descending case. The switching angle is chosen such that the back spoke is vertical yeilding $\theta = 0^\circ$. The equation for the Ascending Potential (AP) is essentially the negative of the DP, given by

$$AP(\theta) = |\vec{r_{Az}}| - |\vec{r_B}z| = |\vec{r_A}| \cdot \text{Cos}[\theta] - |\vec{r_B}| \cdot \text{Cos}\left[\frac{\pi}{3} - \theta\right] \quad (11)$$

For $\theta = 0^\circ$, the maximum AP is 19.75 inches, which is the same height that the robot can descend with the Descending Transition.

For obstacles over 19.75 inches, the robot must use the side of the front spoke as opposed to the bottom of the foot. The feet have been shaped to be able to hook terrain features and have been outfitted with a non-skid surface. However, this ascending case is likely to experience some slip on the front foot contact point as the robot climbs.

Using the Non-Adjacent Spoke Transition, the robot is able to theoretically climb $2\sqrt{3}$ times the nominal walking height, l_{nom}, at a switching angle of $\theta = -30^\circ$. Here the nominal walking height is defined as half the overall spoke length. This height is determined based on $l_{max} = 2 \cdot l_{nom}$ and point contact at the end of the feet.

The theoretical height is not achievable because $l_{max} \neq 2 \cdot l_{nom}$ and the front foot must overshoot the obstacle edge to hook it. The distance that the front spoke must extended past the contact point will be named l_{hook}. The value of l_{hook} must be determined conservatively since a slip while climbing could cause a great deal of impact to the robot. Currently a value of 3 inches is uesd for l_{hook}.

When l_{hook} is taken into account, -30° is no longer the maximum possible obstacle height. $|\vec{r_B}|$ is set to $l_{max} - l_{hook}$ and $|\vec{r_A}|$ is set to l_{max}. Using the law of cosines we can determine the maximum possible height

$$AP^2 = l_{max}^2 + (l_{max} - l_{hook})^2 - 2(l_{max})(l_{max} - l_{hook})Sin(2\beta) \quad (12)$$

where 2β is the angle between the non-adjacent spokes. The maximum AP for this configuration is 30.35 inches. While this gives a maximum climbing height for the ideal condition, we must consider that in reality the robot will not encounter ideal obstacles and will have trouble with exact foot placement in the bottom corner of the obstacle. Additionally, the compliance in the spokes will cause the rear spoke to become shorter under load further reducing the maximum climbing height.

The amount of compliance in the rear spoke can be minimized while allowing for easy foot placement of the back spoke by using $\theta = 0^\circ$. This climbing configuration positions IMPASS with the back spoke vertically. The height that the robot can climb, AP, using this transition is described by the equation

$$AP = |\vec{r_A}| + Sin(30)(|\vec{r_B} + l_{hook}) \quad (13)$$

yielding a value of 27 inches for the current prototype. This means IMPASS can realistically climb obstacles 2.25 times the nominal walking height.

Default Transition, $\theta = 30^\circ$

The previous two sections have discussed ascending and descending configurations. However, many obstacles that IMPASS encounters will be fairly small in size, not requiring any gait adaptation. The gait that best balances moderate obstacles, both positive and negative, is a constant $\theta = 30^\circ$. In this configuration, the slope of both front and back contact spokes is the same. That means that the robot can achieve equal AP and DP during any step. The maximum height change that can be traversed in the Default Transition, $|AP| = |DP|$ is

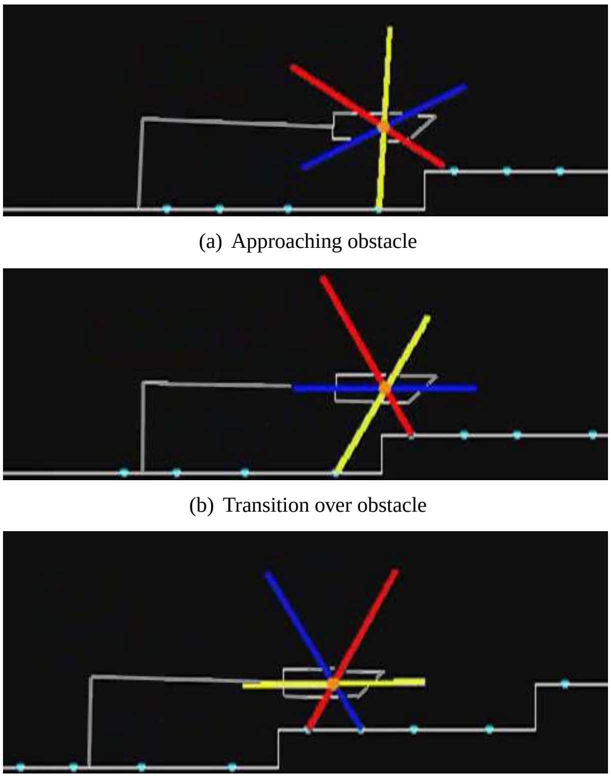
$$|AP| = |DP| = l_{max}Sin(60^\circ) - l_{min}Sin(60^\circ) \quad (14)$$

The maximum obstacle height that can be climbed is 13.4 inches. Having such flexible height change characteristics is very valuable. Sensor data can change at a moments notice, springing a positive or negative obstacle into the robot's path that requires changes to the current step. With the Default Transition, the robot is equally ready for a height change in any direction.

This transition also has good stability characteristics. The hub can only extend past the back contact point by distance $\frac{l_{max}}{2}$ at full height. For the current robot, the Default Transition is always stable. In general for a centrally located CG, this transition should be static for most, if not all, of its operating range.

SIMULATION AND EXPERIMENTATION

All of software for the step transitions was initially tuned in a custom built simulator. The simulation environment was created using LabVIEW with the IMAQ toolkit. Motion messages are received by the simulator component and used to create a visual representation of the robot and the terrain as shown in Figure 12. This software made it possible to detect any flaws in the motion planning algorithms when applied to an ideal robot and terrain.

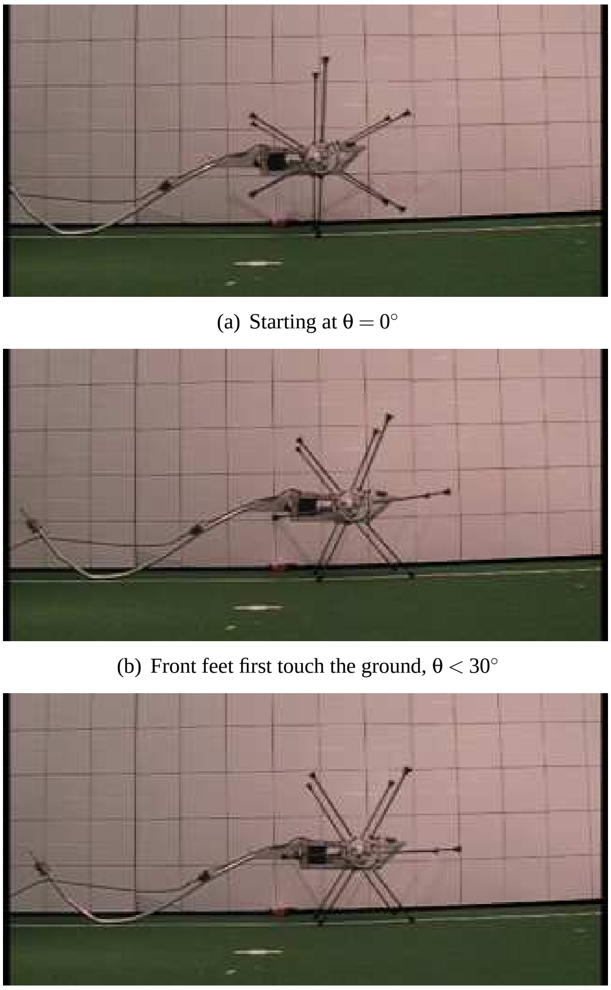


(a) Approaching obstacle

(b) Transition over obstacle

(c) Next transition

Figure 12. SIMULATION TESTING OF THE DEFAULT TRANSITION.



(a) Starting at $\theta = 0^\circ$

(b) Front feet first touch the ground, $\theta < 30^\circ$

(c) Transition complete, $\theta = 30^\circ$

Figure 13. TESTING OF THE DEFAULT TRANSITION. THE FRONT SPOKES TOUCH THE GROUND BEFORE $\theta = 30^\circ$ DUE TO COMPLIANCE IN THE SPOKES AND BACKLASH IN THE HUB GEAR TRAIN.

Of course, ideal conditions rarely exist in the real world. To truly validate an algorithm, it must be tested on hardware. The simulation testing of the motion algorithms showed proper execution of all transition. However, when the algorithm was implemented on the robot there were some inconsistencies. These differences were due to certain physical and mechanical properties of the robot.

The inconsistencies between simulation and experimentation can be seen with the Default Transition in Figure 13. The front spoke contacts the ground prematurely, seen in Figure 13(b). As a result, the robot violated the no-slip condition in order to finally reach the correct transition geometry in Figure 13(c). The discrepancy between the analytical and experimental results was caused by certain properties of the hardware.

There were two major reasons that the robot contacted the ground early. The first reason is that there is noticeable backlash in the hub gear train, which is magnified by the fact it is attached to a long spoke. Angular position of the hub is measured upstream of the gear train, right at the motor. This makes accurate positioning for the hub itself impossible. When the hub center passes over the contact spokes, the gears switch to the other face of their teeth making the robot pitch forward $5^\circ - 10^\circ$.

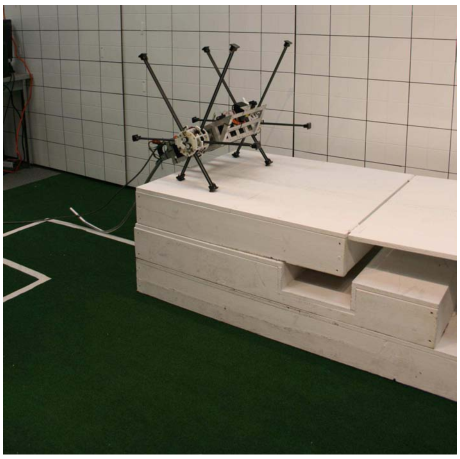
The second factor driving the early ground contact is the compliance of the spokes. The spoke does not radiate in a straight line from the hub when under load. Therefore the rotation of the hub relative to the body is not indicative of the the true rotation of the robot about the contact point, as it has been modeled in the software. As the load on the spoke shifts, the degree of bending changes. This variable deflection would need to be taken into account to achieve an accurate value of hub rotation about the contact point.

The Ascending and Descending transitions still work well despite the early contact. The Non-Adjacent Ascending transition experiment is shown in Figure 14.

The two factors just discussed, spoke compliance and gear train backlash, cause an over-rotation of the hub. The result of this over-rotation is that the front spoke contacts the ground be-

(a) Transition

(b) IMPASS pulls itself onto the obstacle



(c) On top of the obstacle

Figure 14. IMPASS CLIMBING AN 18 INCH OBSTACLE WITH THE NON-ADJACENT ASCENDING TRANSITION.

fore it is supposed to. We then find IMPASS in a two-point contact configuration with the spokes not in their final geometry. To reach the final geometry, one or more of the spokes must slip because the two-point contact kinematics could not be followed. In experiments, we found that both front and back spokes could slip depending on the step. Determining which spoke would slip requires an understanding of the friction forces.

In a two-point contact stance with the tail contacting the ground, we have a statically indeterminate system. The normal forces at the contact points depend on the stiffness of the members. The tail is very stiff, while the stiffness in the spokes varies significantly with their orientation and length. Depending on where the front spoke touches the ground with respect to the desired contact point, the stiffness can significantly vary. With the current transition, the spoke is contacting the ground before the desired contact point, making it shorter and more vertical than planned; therefore it is more stiff. Because of the increased stiffness in the front spoke for the experimental transition, there is more friction to prevent slip. The back spoke would then be more likely to slip.

If either of the two spokes were to slip, it is preferred that the front spoke slips. The back contact point is the reference for future steps. If this contact point is moved the robot will loose accurate localization, potentially causing a foot to be misplaced on a critical terrain feature. There are two basic solutions that can prevent the over-rotation of the hub resulting in slip of the back contact point. One is to build a model to predict actual hub position based on mechanical and physical properties of the robot. The second method is to plan the gait such that the front contact point will slip instead of the back contact point.

If a better position estimate for the hub was available, the motion planning software would be able to touch the front spoke to the ground at the ideal point. To get an accurate value for the rotation about the contact point, a model of the gear train backlash and spoke compliance would need to be built. Such a model is not included in the scope of this paper, but would be an attractive option for future research.

A fairly simple software solution was devised to prevent slip of the back spoke by always slipping the front spoke. By extending the front spoke past its desired transition length in advance of the transition, it will prematurely contact the ground beyond the desired contact point and prevent the over-rotation of the hub. Adding additional support spokes helps increase accuracy of position readings by reversing the gear train backlash and reducing compliance in the back spoke. The difference between this spoke pre-extension and the current algorithm is that the front spoke is always longer and at a shallower angle than the back spoke. The back spoke does not slip because there is more normal force acting on it. While this solution violates the no-slip criteria, it does produce a practical solution to the mechanical problems encountered with this transition.

CONCLUSION

This paper has discussed the gaits and transitions for the IMPASS robot, which can be used in motion planning algorithms for intelligent control. Transitions can be described by the angle that the back spoke makes with the z-axis, given as θ, or the angle that the back spoke makes with the line normal to the ground link, d_g, given as θ_2. There are infinite number of angles that the robot can switch at. For the one-point contact gait, climbing and descending large obstacles is best done with angles of 0° and 60° respectively, because the extended spoke is oriented vertically. The compliance in the spokes and gear train backlash is least prevalent with vertically oriented spokes. There are two configurations in which IMPASS can climb, one using an adjacent spoke and the other with a non-adjacent spoke. In the non-adjacent spoke configuration, the forward spoke is used to actually pull IMPASS up onto the obstacle. This configuration can be used to climb much higher obstacles that the adjacent spoke climbing case. For normal walking, a switching angle of 30° was chosen because it can achieve a future contact point that is either higher or lower with equal ability. Using these transitions assists IMPASS in determining an intelligent method for traversing terrain.

There is still much work that can be accomplished with the IMPASS platform. It would be beneficial to develop a more accurate wheel rotation model based on compliance of the spokes and backlash in the hub gear train. The motion planning considerations discussed in this paper can be applied to intelligent motion planning algorithms, first in the two-dimensional sagittal plane, then expanded to three dimensions. To assist in this motion planning, it would be very useful to implement a perception suite on IMPASS with Simultaneous Localization and Mapping (SLAM). Once outfitted with proper motion planning and perception, IMPASS has the potential to be a very useful platform for search and rescue, reconnaissance, or anti-terror response.

ACKNOWLEDGMENT

The authors would like to thank the National Science Foundation (NSF) for their support of this project under grant No. IIS-0535012. Additionally, the authors are appreciative of the hard work set forth by the 2007 and 2008 Virginia Tech senior design teams in their building of the IMPASS prototype.

REFERENCES

[1] Quinn, R. D., Nelson, G. M., Bachmann, R. J., Kingsley, D. A., Offi, J. T., and Ritzmann, R. E., 2001. "Insect Designs for Improved Robot Mobility". *Climbing and Walking Robots Conference pp. 69-76, Karlsruhe, Germany*.

[2] Quinn, R. D., Offi, J. T., Kingsley, D. A., and Ritzmann, R. E., 2002. "Improved Mobility Through Abstracted Biological Principles". *IEEE International Conference on Intelligent Robots and Systems, Lausanne, Switzerland*.

[3] Moore, E., 2002. "Leg Design and Stair Climbing Control for the RHex Robot Hexapod". *Thesis submitted to the Mechanical Engineering Department at McGill University, Montreal, Canada*.

[4] Saranli, U. "Summary of the RHex robot platform". *Web: www.rhex.web.tr*.

[5] Laney, D., and Hong, D., 2005. "Kinematic Analysis of a Novel Rimless Wheel with Independently Actuated Spokes". *ASME International Design Engineering Technical Conferences Long Beach, California, USA*.

[6] Hong, D., and Laney, D., 2006. "Preliminary Design and Kinematic Analysis of a Mobility Platform with Two Acutated Spoke Wheels". *UKC*.

[7] Ren, P., W. Y., and Hong, D., 2008. "Three-dimensional Kinematic Analysis of a Two Actuated Spoke Wheel Robot Based on its Equivalency to a Serial Manipulator". *32nd ASME Mechanisms and Robotics Conference Brooklyn, New York, USA*.