Adaptable Gait Generation for Autotomised Legged Robots

Gustavo Schleyer, R. Andrew Russell
Intelligent Robotics Research Center,
Clayton campus,Monash University,VIC 3800,AUSTRALIA
gustavo.schleyer@monash.edu, andy.russell@monash.edu

Abstract

This paper presents an adaptable gait generation method which allows legged robots to walk in a stable fashion after they have shed a combination of legs. By using this technique, robots will be able to continue with their mission even after a combination of their legs has been damaged. The method selects and calculates the final coordinates of a robot's stance and swing legs by maximising the stable mobility of the robot in the direction of locomotion. As a result, stable straight line locomotion in any desired direction has been generated. In addition, the resulting gaits can accommodate a range of loads carried by the robot. The proposed technique has been tested in a hexapod robot, but results can be extended to robots with any number of legs. Finally, this method intends to reduce the current gap between biological and robot locomotion, extending robots' resilience to damage and improving autonomy.

1 Introduction

Autonomous robot locomotion is an important area of robotics. It plays a key role in robots that must perform exploration or rescue missions. In some cases, such as in extraterrestrial exploration or other hostile environments, human intervention is difficult or impossible. Therefore, the success of this kind of mission is determined by the robots' grade of autonomy. This is often related to the robots' capacity to traverse unstructured terrain. A number of means of locomotion (e.g. tracks, wheels, legs) have been employed to achieve this task. However, legged locomotion presents advantages over other methods, such as: it is adaptive to uneven terrain, uses isolated footholds, provides active suspension and causes less environmental effects than wheeled or tracked locomotion [Hardarson, 1997]. A survey including two-, four- and six-legged robots can be found in [Pfeiffer et al., 1998]. Being surrounded by legged creatures able to travel across irregular terrain, it was only a matter of time before researchers realise that many of the answers to robot locomotion's problems lie in biology. So they began to include some biological principles in the mechanics and control of their robots [Allen et al., 2003; Arena, 2007; Dillmann, 2007; Ljspeert, 2008; Wu et al., 2009]. In fact, biological creatures and robots deal with similar problems during locomotion. Both of them are affected by gravity, energy consumption and must avoid obstacles in a changing environment. In extreme cases, such as when they are escaping from a predator or fouled moulting event, some animals are able to shed parts of their body. This is called autotomy [Maginnis, 2006; McVean, 1975]. For instance, Fig. 1 shows a fly that has autotomised one of its legs.

Fig. 1. Five legged fly.
(Reproduced by permission of Bill Kennedy)

After a leg loss, these kinds of creatures are able to adapt their gait to the new configuration of their body without a learning process. On the other hand, despite the fact that some research has been conducted in this direction [El Sayed et al., 2006; Inagaki, 1997; Spenneberg et al., 2004], to date robots are not able to generate a stable gait which can compensate for an arbitrary combination of leg losses. Therefore, if one or more of a robot's legs are damaged during its mission, the robot probably will not be able to complete it. The proposed technique addresses this problem, considering the loss of an arbitrary combination of legs while maximising the stable locomotion of robots in the direction of locomotion. Depending on the number of available legs, the method introduced in this paper has generated gaits commonly found in nature. For instance, the tripod gait normally found in insects has been generated for robots that have six functional legs.

This paper is organized as follows. An adaptable gait generation method is presented in Section 2. Then, simulated, as well as practical results obtained from the application of this technique in a physical robot, are introduced in Section 3. Finally, conclusions and future related work are discussed in Section 4.

2 Adaptable Gait Generation Method

In general, the gait generation in a robot capable of shedding its legs must be suitable for all the possible leg configurations. Once the robot has autotomised one or more of its legs, it must continue walking with its remaining hardware resources. In addition, the gait must be flexible enough to be able to deal with complex terrain and unexpected obstacles. Another two major aspects that should be considered in any proposed gait are stability and mobility. The robot's relative stability is ensured only if the vertical projection of its centre of mass on the ground plane (from now on simply referred to as robot's centre of mass) is inside the convex hull formed by the vertical projection of the points of contact of the supporting legs on the ground plane. Therefore, stability can only be maintained if there are at least three legs on the ground. For the moment, only a horizontal ground plane has been considered. Future work in this direction will include tilted ground planes.

Initially the intact robot has six legs, which have been named as shown in Fig. 2. The legs' position is established using the Cartesian coordinate system located on the robot, with its positive z axis pointing out of the paper plane and with its positive y axis pointing in the direction of the front of the robot, as is also shown in the figure.

Considering the case when one leg is missing, then there are 10 possible combinations of supporting triangles of legs that can be formed from those still attached to the robot. Overall, the number of possible triangles is determined by (1), performing combinatorial calculations between n_{legs}, the total number of available robot's legs, and 3, the number of supporting legs that form the triangle.

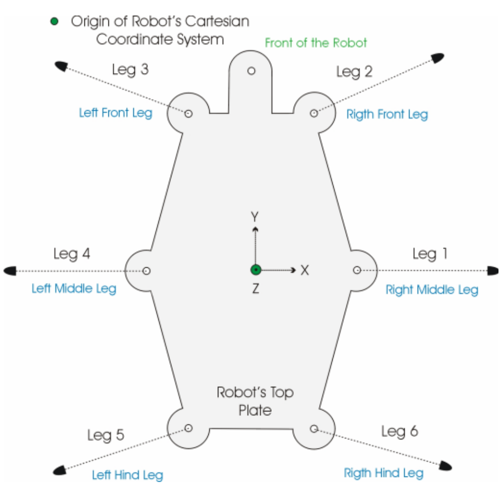

Fig. 2. Robot's Cartesian coordinate system and initial robot's leg configuration.

$$\boldsymbol{n^\circ\ of\ triangles = n_\Delta = C(n_{legs}, 3)} = \frac{n_{legs}!}{3(n_{legs}-3)!} \quad (1)$$

In general, the set of available robot's legs can be defined as $L_{available} = \{l_1, l_2, \dots, l_n\}$, where each l is a number that represents the corresponding available leg. For instance, if $L_{available} = \{2,3,5,6\}$, in this case the value $l_1 = 2$ indicates that Leg 2 is one of the available legs. Then, the set S of all the possible supporting tripods contained in $L_{available}$ is represented by equation (2).

$$S = \{s_1, s_2, \dots, s_{n_\Delta}\} \quad (2)$$

Where

$s_i = \{l_{k1}, l_{k2}, l_{k3}\}$.
$i = 1,2, \dots, n_\Delta$.
$k_1 = 1,2, \dots, n_{legs} - 2$.
$k_2 = k_1 + 1, k_1 + 2, \dots, n_{legs} - 1$.
$k_3 = k_2 + 1, k_2 + 2, \dots, n_{legs}$.

However, not all of the elements of S represent leg tripods which provide a stable support for the robot. Therefore, only the stable tripods, those which enclose the robot's centre of mass, are selected. Then, the set of stable leg triangles can be defined by means of (3).

$$\Delta = \{s | s \in S \wedge s\ is\ a\ stable\ tripod\} \quad (3)$$

Considering that no collinear points can enclose the robot's centre of mass, each element of Δ represents a set of three legs that form a stable supporting triangle. The position of the tips of these legs corresponds with the location of the triangle's vertexes in the robot's Cartesian coordinate system. Finding the most suitable triangle for supporting the robot and calculating the final coordinates of both stance and swing legs in order to maximise stable robot mobility are the main tasks of the proposed gait generation approach.

2.1 Six Legs Gait Generation

The first step in the proposed six legs gait generation algorithm is to find all the possible triangles formed with the available robot legs and verify if the robot's centre of mass is located inside these triangles. Once all the unstable triangles are discarded, relative stability is guaranteed if any of the remaining triangles is selected as the supporting legs. Then, a measure of relative stability of each triangle is calculated. This is simply the distance d_{Δ_stable} between the robot's centre of mass and the respective triangle's centroid.

In the second step, the distance d_{stance_stable} between the robot's centre of mass and the side of each stable triangle in the direction of locomotion is calculated. During the stance phase, the maximum distance that the triangle formed by the supporting legs can be moved whilst it still contains the robot's centre of mass is determined by d_{stance_stable}. However, this distance might be larger than the available backward mobility of the stance legs. Hence, it is necessary to calculate the backward mobility of each triangle, which is the minimum distance d_{stance_mob} between the current position and the posterior extreme position (PEP) of its legs. Then, the stance legs triangle Δ^*

can be established by means of the expression (4) and the set Δ', composed by all the elements of Δ whose d_{stance_stable} and d_{stance_mob} are different from zero.

$$stance\_legs = \Delta^* | \Delta^* \in \Delta' \wedge \forall_i \in \Delta', \quad \frac{d^*_{\Delta\_stable}}{min(d^*_{stance\_stable}, d^*_{stance\_mob})} \le \frac{d_{\Delta\_stable_i}}{min\left(d_{stance\_stable_i}, d_{stance\_mob_i}\right)} \quad (4)$$

Where $i = 1,2,\dots, number\ of\ elements\ of\ \Delta'$.

The final (x, y) coordinates of the stance legs, the position of the legs once their stance cycle has concluded, are determined by means of (5).

$$\begin{bmatrix} x_{final\_stance\_coord} \\ y_{final\_stance\_coord} \end{bmatrix} = \begin{bmatrix} x_{initial\_stance\_coord} \\ y_{initial\_stance\_coord} \end{bmatrix} + \begin{bmatrix} min\left(d^*_{stance\_stable} - \varepsilon, d^*_{stance\_mob}\right)\cos(\theta + \pi) \\ min\left(d^*_{stance\_stable} - \varepsilon, d^*_{stance\_mob}\right)\sin(\theta + \pi) \end{bmatrix} \quad (5)$$

Where θ is the robot movement heading, $\pi/2$ for straight ahead walking. The ε parameter is utilised in order to avoid the robot's centre of mass lying exactly on one side of the stance legs triangle, which could lead to an unstable condition. This would be the case if $\varepsilon = 0$ when $d^*_{stance\_stable}$ is less than $d^*_{stance\_mob}$ and the stance triangle is moved to the limit of stable mobility. In this work $\varepsilon = 5$ has been adopted, meaning that in the worst case the stance legs will be 5 mm inside the outer limit of the stance triangle.

The θ angle allows the robot to change its direction of locomotion without rotating. This may be useful when the robot is walking in constrained spaces. However, this method presents two drawbacks. The first one is that if some of the robot's sensors are intended for forward locomotion, then some sensorial information may be lost. The second one is that the legs' mobility may be reduced when the robot is not walking in the direction for which was designed. As a result, the robot's locomotion could be slower.

A top view of a selected stance legs triangle and the respective swing legs triangle are showed in Figs. 3 and 4. Some of the parameters utilised by equations (4) to (6) are also illustrated in these figures. In both of them the θ value is around $4\pi/9$ (or 80^o). Therefore, in this case, the robot is heading forwards but with a slight inclination to the right (in the opposite direction of the cyan arrow in Fig. 3 or in the direction of the cyan arrow in Fig. 4).

The position of the robot's centre of mass depends on the hardware structure, in this example it coincides with the origin of the robot's coordinate system, for simplicity.

The swing legs are simply determined as the remaining available legs once the stance legs are known. When the robot still has six functional limbs, the final coordinates of the swing legs are established by considering the minimum distance d_{swing_mob} between the current position of the swing legs and their respective anterior extreme position (AEP), and the maximum distance d_{swing_stable} that the triangle formed by these legs can be moved towards the opposite direction of locomotion whilst still containing the robot's centre of mass. This assures the existence of a stable triangle when the swing legs finish their cycle and become stance legs.

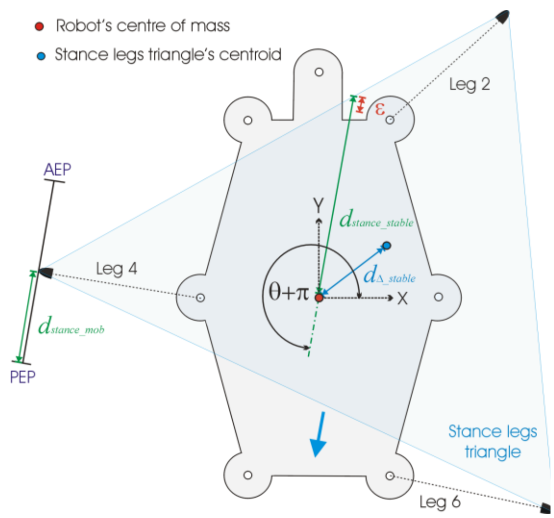

Fig. 3. Top view of a stance legs triangle including related parameters.

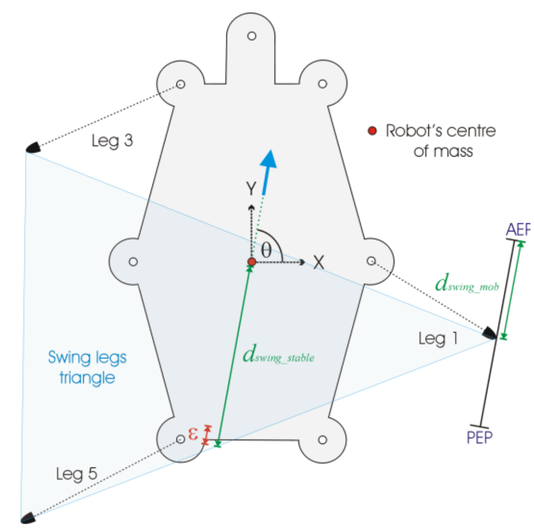

Fig. 4. Top view of a swing legs triangle including related parameters.

The final (x, y) coordinates of the swing legs, the position of the legs once their swing cycle has concluded, are calculated as follows.

$$\begin{bmatrix} x_{final\_swing\_coord} \\ y_{final\_swing\_coord} \end{bmatrix} = \begin{bmatrix} x_{initial\_swing\_coord} \\ y_{initial\_swing\_coord} \end{bmatrix} + \begin{bmatrix} min\left(d^*_{swing\_stable} - \varepsilon, d^*_{swing\_mob}\right)\cos(\theta) \\ min\left(d^*_{swing\_stable} - \varepsilon, d^*_{swing\_mob}\right)\sin(\theta) \end{bmatrix} \quad (6)$$

2.2 Five Legs Gait Generation

The basic strategy employed in the five legs gait generation is analogous to the one described in the previous section. However, once three stance legs have been selected, there are only two remaining swing legs. Thus, it is unfeasible to immediately form the triangle of supporting legs for the next cycle. In this case, one of the stance legs must be selected in order to calculate the final (x, y) coordinates of the swing legs triangle by means of (6). This is achieved by evaluating all of the possible stable triangles, constituted by the two swing legs and each one of the stance legs, in (4). Determining the future supporting legs in this way means that once again stability and mobility are the employed criteria. The resulting gait has two stages. First, the three initial stance legs are moved against the direction of locomotion, towards their final coordinates calculated by (5). At the same time, the two swing legs are moved in the opposite direction, towards the coordinates determined by (6). In this calculation, the information about the position of the selected third swing leg, at the beginning of its stance phase has been employed, but the current movement of the leg is still governed by its stance phase. In the next stage, once all the legs have reached their target coordinates, the stance leg selected as the third swing leg is moved in the same direction as that previously followed by the two initial swing legs. In this stage there is no forward motion, only the third swing leg is moved whilst there are four legs supporting the robot. Once this leg reaches the coordinates specified by (6), the cycle starts again with stance legs becoming swing legs and vice versa.

2.3 Four Legs Gait Generation

A similar approach to the one previously discussed for five legs can be adopted for gait generation when there are only four functional legs. In this case, the stance legs are also calculated by equation (4). Nonetheless, there is a slight difference with respect to how the final coordinates of both stance and swing legs are established. If these coordinates were determined by means of (5) and (6), respectively, there would be a point where the only stable triangle that could be selected as stance legs had no mobility at all. In order to avoid this situation, observations of quadruped gaits, particularly in the elephant, have been conducted. The main elephant gait feature incorporated in the four legs robot gait is that each elephant leg stays in stance phase until the remaining three legs have experienced the swing phase, moving the stance legs on each step only about one third of their available backward mobility. Consequently, the backwards mobility of the robot stance legs has been restricted to be equal or less than a third of max_{mob}, the maximum backwards mobility of all the robot's legs (please, refer to Fig. 5).

This value is calculated at the beginning of the locomotion or every time the four legs have experienced the swing phase. Once max_{mob} has been determined, the target stance legs and swing leg coordinates are established by means of (7) and (8), respectively.

$$\begin{bmatrix} x_{final\_stance\_coord} \\ y_{final\_stance\_coord} \end{bmatrix} = \begin{bmatrix} x_{initial\_stance\_coord} \\ y_{initial\_stance\_coord} \end{bmatrix} + \begin{bmatrix} min\left(d^*_{stance\_stable} - \varepsilon, d^*_{stance\_mob}, \frac{max_{mob}}{3}\right)\cos(\theta + \pi) \\ min\left(d^*_{stance\_stable} - \varepsilon, d^*_{stance\_mob}, \frac{max_{mob}}{3}\right)\sin(\theta + \pi) \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} x_{final\_swing\_coord} \\ y_{final\_swing\_coord} \end{bmatrix} = \begin{bmatrix} x_{home\_swing\_coord} \\ y_{home\_swing\_coord} \end{bmatrix} + \begin{bmatrix} \frac{max_{mob}}{2}\cos(\theta) \\ \frac{max_{mob}}{2}\sin(\theta) \end{bmatrix} \quad (8)$$

Where $x_{home\_swing\_coord}$ and $y_{home\_swing\_coord}$ represent the home position coordinates of the robot legs, which correspond with the middle point between the respective AEP and PEP.

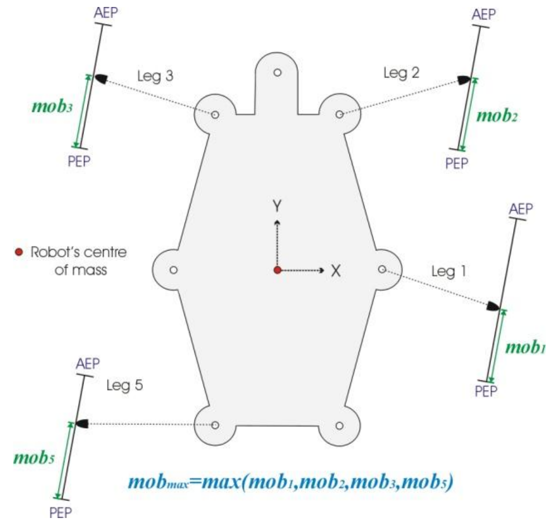

Fig. 5. Calculation of max_{mob}.

One difference between (6) and (8) in the determination of the final coordinates of the swing legs is that in (8), the stability of possible triangles formed with a given swing leg is not considered in the calculation of its coordinates. This is unnecessary because, in the proposed four legs gait, sending the swing legs to their AEP results in the creation of stable stance triangles. However, this is not absolutely true at the beginning of the locomotion, when the four legs are in their home position and must initiate the gait cycle. In order to maintain the gait stability each step must be short at the beginning, and then becoming gradually larger until the regular gait has been reached. This is also accomplished by means of the max_{mob} value, which maintains an equilibrium between the backward and forward movement of stance and swing legs, respectively.

2.4 Gait Generation with Fewer Legs

The three legs gait generation is analogous to the six legs gait generation. The difference is that here there is only one possible triangle which constitutes the stance and swing legs alternately. When the legs are in the stance phase the robot is lifted and the legs are moved backwards according to equation (5). Then, the robot is lowered to the ground and the legs start their swing phase. In this stage the legs are moved forwards using (6). Finally, the legs start their stance phase again, lifting the robot and beginning a new stance-swing cycle.

With two or one leg, there is no stable feasible gait. However, if a point on the bottom plate of the robot is considered as a third leg, it is possible to generate a gait similar to the one for three legs. The difference here is that this kind of locomotion, which resembles a paddling movement, involves dragging the body of the robot. Hence, the robot's bottom plate must be designed accordingly, minimising the friction with the terrain and being robust enough to undergo dragging. Once the vertexes of the stance triangle have been identified, the robot rotates until its centroid is closer than the dragging point to the target location, whilst both are located on the straight line defined by the direction of locomotion. Finally, equations (5) and (6), and the same sequence of movements described for the three legs gait generation can be employed to generate the gait.

When there is only one leg remaining, the robot is rotated until the dragging point is closer than the robot's centre of mass to the target location, whilst both are located on the straight line defined by the direction of locomotion. In this case, the whole bottom plate of the robot's body is dragged. During the swing phase, the leg is moved forwards to its AEP aligned with the direction of locomotion. Then, during the swing phase, the leg is moved towards the robot's body until it reaches its PEP.

3 Experimental Results

3.1 Simulated Results

This section shows the simulation results of the gait generation described in sections 2.1 to 2.3. The results are presented in tables which specify the robot's stance legs (in black) and swing legs (in white) in each step (for the correspondence between leg number and leg position in the robot, please refer to Fig. 2). Until now, all the generated gaits are periodic. Therefore, the tables show all the steps belonging to one period. The generated gait has been obtained by considering that the robot's centre of mass is on the origin of the robot's coordinate system. Besides, it has been assumed that all the robot's legs are in their home position at the beginning of the gait generation.

Table 1 shows the generated gait for a six legged robot. The results show that a tripod gait has been obtained, which is commonly utilised by hexapod creatures.

Table 1. Six Legs Gait Generation.

	Step	1	2
Leg	1	■	□
	2	□	■
	3	■	□
	4	□	■
	5	■	□
	6	□	■

Tables 2 to 7 contain the generated gait for the robot after it has lost one of its legs. Each table corresponds to the generated gait after a different robot's leg has been lost.

The results for the five legs gait generation show a periodic gait composed by 4 steps. During steps 2 and 4 only the swing leg is moved, the four stance legs stay still supporting the robot. Therefore, the robot is supported alternately by 3 and 4 legs. Table 4 shows a special case where the robot takes two steps before actually starting the period of steps. These steps are called *initial steps* due to the fact that they are taken only once at the beginning of the gait generation. The stance legs during the *initial steps* are represented by grey colour in Table 4 and in all of the tables where *initial steps* are present. Another particularity of the gait contained in Table 4 is that this is the only one that alternates the swing leg of steps 2 and 4.

Table 2. Five Legs Gait Generation (Leg 1 Lost).

	Step	1	2	3	4
Leg	2	■	□	■	□
	3	□	■	■	■
	4	■	■	□	■
	5	□	■	■	■
	6	■	■	□	■

Table 3. Five Legs Gait Generation (Leg 2 Lost).

	Step	1	2	3	4
Leg	1	■	□	■	□
	3	■	■	□	■
	4	□	■	■	■
	5	■	■	□	■
	6	□	■	■	■

Table 4. Five Legs Gait Generation (Leg 3 Lost).

	Step	1	2	1	2	3	4
Leg	1	□	▒	■	□	■	■
	2	▒	□	■	■	□	■
	4	▒	▒	□	■	■	□
	5	□	▒	■	■	□	■
	6	▒	▒	□	■	■	■

Table 5. Five Legs Gait Generation (Leg 4 Lost).

	Step	1	2	3	4
Leg	1	■	■	□	■
	2	□	■	■	■
	3	■	□	■	□
	5	■	■	□	■
	6	□	■	■	■

Table 6. Five Legs Gait Generation (Leg 5 Lost).

	Step	1	2	3	4
Leg	1	□	■	■	■
	2	■	■	□	■
	3	□	■	■	■
	4	■	□	■	□
	6	■	■	□	■

Table 7. Five Legs Gait Generation (Leg 6 Lost).

	Step	1	2	3	4
Leg	1	■	□	■	□
	2	□	■	■	■
	3	■	■	□	■
	4	□	■	■	■
	5	■	■	□	■

Tables 8 to 16 contain the generated gait for the robot after it has lost two of its legs. Each table corresponds to the generated gait for a different combination of 4 legs. The combinations that consider the lost of two legs at the same side of the robot are not included at the moment. This is because it is not possible to generate a stable gait with these leg configurations for the current experimental robot. However, this problem will be solved with a new version of the experimental robot. The solution is to move one leg of the robot's side that has three legs to the opposite side.

Therefore, the resulting leg configuration will be similar a one of the contained in Tables 8 to 16 and a stable gait will be generated without changing the proposed algorithm.

Table 8. Four Legs Gait Generation (Leg 1 and 3 Lost).

	Step	1	2	3	1	2	3	4
Leg	2							
	4							
	5							
	6							

Table 9. Four Legs Gait Generation (Leg 1 and 4 Lost).

	Step	1	2	3	1	2	3	4
Leg	2							
	3							
	5							
	6							

Table 10. Four Legs Gait Generation (Leg 1 and 5 Lost).

	Step	1	2	3	1	2	3	4
Leg	2							
	3							
	4							
	6							

Table 11. Four Legs Gait Generation (Leg 2 and 3 Lost).

	Step	1	2	3	4	5	6	7	1	2	3	4
Leg	1											
	4											
	5											
	6											

Table 12. Four Legs Gait Generation (Leg 2 and 4 Lost).

	Step	1	2	3	1	2	3	4
Leg	1							
	3							
	5							
	6							

Table 13. Four Legs Gait Generation (Leg 2 and 5 Lost).

	Step	1	2	3	4
Leg	1				
	3				
	4				
	6				

Table 14. Four Legs Gait Generation (Leg 3 and 6 Lost).

	Step	1	2	3	4
Leg	1				
	2				
	4				
	5				

Table 15. Four Legs Gait Generation (Leg 4 and 6 Lost).

	Step	1	2	3	1	2	3	4
Leg	1							
	2							
	3							
	5							

Table 16. Four Legs Gait Generation (Leg 5 and 6 Lost).

	Step	1	2	3	1	2	3	4
Leg	1							
	2							
	3							
	4							

The results for the four legs gait generation show a periodic gait composed by 4 steps. In this case, the generation of *initial steps* is more frequent. They allow the stable transition from the home position of the robot's legs to the position established by the periodic gait. In general, only 3 *initial steps* are enough. Nevertheless, Table 11 contains a gait where 7 *initial steps* were generated. In the other hand, the gaits contained in Tables 13 and 14 only generate periodic steps.

This section has shown the generation of different stable gaits using the theory explained in sections 2.1 to 2.3. All the generated gaits are periodic, but the number of steps of each period depends on the available number of robot's legs. The simulation shows that the proposed approach generates a stable gait from almost any leg configuration which includes between 4 and 6 legs.

3.2 Hexapod Robot

The theory previously discussed has been tested in a physical robot shown in Fig. 6. Currently, the chassis of a MSR-H01 Hexapod, manufactured by Micromagic Systems, is being utilised. In the future, this will be replaced by a robot exclusively designed for this project.

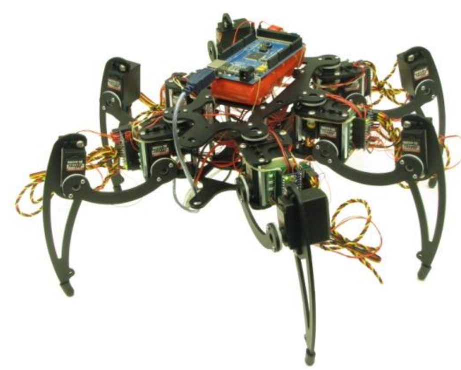

Fig. 6. Experimental Hexapod Robot

The robot central control is performed by an Arduino Mega microcontroller (located on the top of the robot in Fig. 6). In addition, six Arduino Pro Mini microprocessors, located on each of the robot's legs, perform local tasks. These microcontrollers interchange information with the robot's central microprocessor utilising an I^2C (Inter-Integrated Circuit) communication bus. Each leg microcontroller is connected to a printed circuit board specially designed for the project. Basically, each leg's P.C.B. integrates the operation of the leg's microcontroller, the leg's sensors and the communication with the central control. The outputs of each leg's microcontroller are the PWM control signals of the leg's servo motors, on/off signals of 3 multi-purpose LEDs and a signal that will activate a leg release system which is still in its design stage. This system will allow the robot to electrically and mechanically disconnect one or more legs when necessary. For instance, if a leg malfunction prevents the robot walking in a stable fashion.

Currently, two kinds of sensors have been utilised in the generation of the gait. Force sensors measure the pulse width of the PWM voltage signal controlling each one of the leg's servo motors. The pulse width is directly proportional to the error between the current and the target servo positions. Therefore, if an external force prevents a servo from reaching its target position, then the pulse width associated with the resulting error can be used to calculate the external force magnitude. The information provided by this sensor is utilised in the robot's centre of mass calculations. In addition, position sensors measure the voltage from the servo's internal potentiometer, which is directly proportional to the servo position. Currently this is the most accurate feedback provided by the sensing system about the servo's actual position. Information provided by these sensors is employed in the proportional control that governs the robot legs during the three legs gait generation. In this case is necessary to lift the robot with only three legs, which requires more torque than the robot's servo motors normally provide. By using this sensor it is possible to know if the servos are not reaching the specified coordinates. If this is the case, the servos are commanded to go to a further coordinate, which increments the error between their current and their desired position. As a result, the torque of the servo motors is incremented and the robot is lifted.

Fig. 7 shows the experimental robot walking by utilising the proposed gait generation method with different numbers of disabled legs. The robot automatically calculates the number of available legs by requesting acknowledge signals from the leg microcontrollers every time that a movement to new coordinates is commanded. If it is not possible to establish communication with a leg during a certain period of time, the robot automatically adapts its gait considering the new number of working legs. As future work, cases where communication with a leg microcontroller works perfectly even after the leg has suffered damage will be considered. For instance, if part of a leg was disabled or bent out of shape, the robot should identify the extent of the damage and determine whether it is convenient to include the limb in the gait or not.

The obtained gaits are the same as previously presented in subsection 3.1. When the robot walks with its six legs the tripod gait is adopted and the robot reaches its fastest speed of locomotion. This progressively diminishes as the robot increments the number of disabled legs.

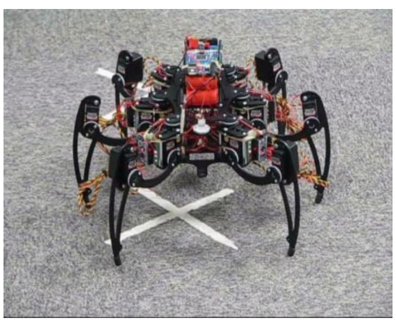

Fig. 7a. Six legs gait generation

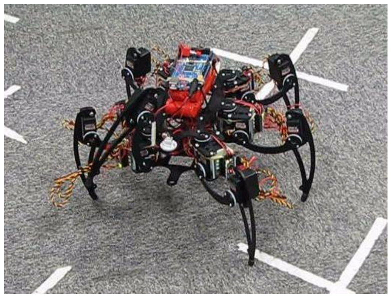

Fig. 7b. Five legs gait generation

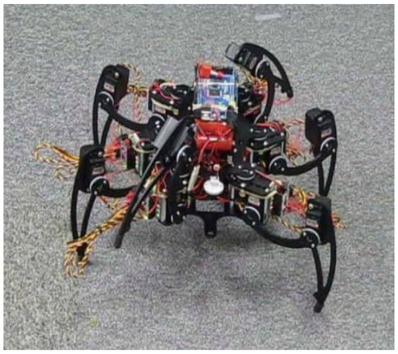

Fig. 7c. Four legs gait generation

Fig. 7d. Three legs gait generation

The robot's stability can be improved by modifying its tilt. By selecting a suitable tilt, the position of the vertical projection of the robot's centre of mass on the ground plane can be moved towards the centroid of the convex hull formed by the robot's supporting legs, improving the robot's relative stability. Another way of improving stability is by moving the robot in parallel to the ground plane in the direction that shortens the distance between the robot's centre of mass and the mentioned convex hull's centroid. After shifting the robot's centre of mass, the direction of locomotion should be modified. So, the final coordinates of the stance legs, and therefore the course of the robot, remain unaltered at the end of each step.

4 Conclusions and Future Work

This paper has presented an adaptable gait generation method that allows damaged or autotomised robots to walk with different combinations of leg losses. The proposed technique maximises the stable mobility of robots once the position of their centre of mass has been calculated. This means that if the position of the robot's centre of mass changes, either because the robot is carrying a load or its hardware configuration has been altered, by using this method the target robot will be still able to generate a stable gait. Instead of proposing a different gait generation method for each possible number of functional legs, the adaptable gait generation technique presented in this paper only requires slight modifications in the equations of the six legs gait generation approach in order to produce stable gaits when fewer functional legs are available. In addition, this approach generates straight line locomotion in any desired direction, which allows the robot to modify its direction of locomotion without actually rotate the robot. This could be useful when is necessary to manoeuvre the robot in reduced spaces.

Future experiments will allow us to analyse the performance of the proposed approach when it is applied in robots walking on unstructured terrain, with different terrain slopes and small obstacles. Furthermore, stability during locomotion will be improved by moving the robot in parallel to the ground plane in the direction that shortens the distance between the robot's centre of mass and the centroid of the convex hull formed by the robot's supporting legs. This technique will be compared with the modification of the robot's tilt in order to determine advantages and disadvantages of both methods when are applied individually or simultaneously. Finally, the proposed adaptable gait generation technique will be tested in robots carrying different combinations of load. These kinds of experiments will require a more accurate calculation of the position of the robot's centre of mass. Therefore, extra sensors will be utilised in this endeavour.

References

[Allen et al., 2003] Allen, T.; Bachmann, R.; Kingsley, D.; Nelson, G.; Offi, J. and Quinn, R., "Parallel Complementary Strategies For Implementing Biological Principles Into Mobile Robots", *The International Journal of Robotics Research*, Vol. 22, No. 3, 2003, pp. 169-186.

[Arena, 2007] Arena, P.; Patane, L.; Schilling, M. and Schmitz, J., "Walking capabilities of Gregor controlled through Walknet", *Proceedings of SPIE, The International Society for Optical Engineering*, Vol. 6592, 2007.

[Dillmann, 2007] Dillmann, R.; Albiez, J.; Gaßmann, B.; Kerscher, T. and Zöllner, M., "Biologically Inspired Walking Machines: Design, Control and Perception". *Philosophical Transactions of the Royal Society A 365*, (2007), pp.133-151.

[El Sayed et al., 2006] El Sayed Auf, A.; Mösch, F. and Litza, M., "How the Six-legged Walking Machine OSCAR Handles Leg Amputations", Proceedings of the Workshop on Bio-Inspired Cooperative and Adaptive Behaviours in Robots at the SAB IX, Rome 2006.

[Hardarson, 1997] Hardarson, F., "Locomotion for difficult terrain. A survey study", Technical Report, Mechatronics Division, Department of Machine Design, Royal Institute of Technology, Stockholm, Sweden, 1997.

[Inagaki, 1997] Inagaki, K., "Gait study for hexapod walking with disabled leg", Proceedings of the 1997 IEEE/RSJ International Conference on Intelligent Robots and Systems, Vol. 1, 1997, pp. 408-413.

[Ljspeert, 2008] Ljspeert, A., "Central pattern generators for locomotion control in animals and robots: a review", *Neural Networks*, Vol. 21, No. 4, 2008, pp. 642-653.

[Maginnis, 2006] Maginnis, T., "The costs of autotomy and regeneration in animals: a review and framework for future research", *Behavioral Ecology*, Vol. 17, No. 5, June 2006, pp. 857–872.

[McVean, 1975] McVean, A., "Autotomy: Mini-review", Comparative Biochemistry and Physiology, Vol. 51, No. 3, 1975, pp. 497–505.

[Pfeiffer et al., 1998] Pfeiffer, F.; Josef, S. and Roßmann, T., "Legged walking machines", Autonomous Robotic Systems, Vol. 236, Springer Berlin / Heidelberg, 1998, pp. 235-263.

[Spenneberg et al., 2004] Spenneberg, D., McCullough, K., and Kirchner, F., "Stability of Walking in Multilegged Robot Suffering Leg Loss", Proceedings ICRA '04, IEEE International Conference on Robotics and Automation, May 2004, vol. 3, pp. 2159-2164.

[Wu et al., 2009] Wu, Q.; Liu, C.; Zhang, J. and Chen, Q., "Survey of locomotion control of legged robots inspired by biological concept", *Science in China Series F: Information Sciences*, Vol. 52, No. 10, October 2009, pp. 1715-1729.