DYNAMIC GAIT CHANGING FOR HEXAPOD WALKING ROBOTS

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ABSTRACT

A method of changing between periodic walking patterns (or *gaits*) for a six legged robot is presented. By changing these patterns, the walking speed of the robot will also change. The proposed method was designed for robots that use one degree-of-freedom (DOF) per leg for walking, or that have a fixed distance that the legs remain on the ground (i.e. the stride length). It has been found for such robots that they can only change between gaits by modifying the time that the legs remain in the air. A control system to generate these changing gaits is also presented. The method and algorithm described can also be applied to other robots that have two or more DOF per leg.

Keywords: Robot control, Locomotion, Walking robot, Entomology.

INTRODUCTION

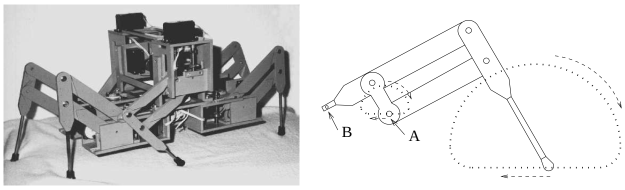
In the last ten years or so we have seen an increase in the number of mechanical walking robot designs. In particular, six legged robots (or hexapods) have been very popular. The ability to traverse rough terrain allows walking machines to be very useful. Both large and small walking robots are being developed for various applications from forestry inspection [1] to space exploration [2], or simply for research purposes.

Rough terrain walking requires a robot's leg to have at least two DOF to allow a leg to move forward or backward and lift over objects. Also, the *stride* length (the distance that the foot travels while it is on the ground) of each leg can therefore be variable.

It is possible however, to use only one rotational DOF per leg to make a robot walk, although walking would be restricted to flat surfaces. A separate DOF is required to lift the leg. If only one rotational DOF is to be used, then the circular motion must be modified by a mechanism to produce a fixed semicircular trajectory to propel the robot and lift the leg sequentially.

The main focus of this paper describes how to dynamically change between periodic walking patterns for robots that use one DOF per leg in order to walk. There are a range of periodic gaits that are used by insects such as the *Blaberus discoidalis*, the *Carausius Morosus* and various beetles. There are patterns that allow the insects to walk slowly or fast. A robot that is programmed to walk using a particular known gait requires a method to modify the walking pattern to allow changing from one gait to another. This would allow the robot to dynamically change it's walking speed.

The mechanical platform used to perform the experiments is shown in Figure 1(a). This hexapod robot (named "Strider") was developed in the course of this research and is described in detail in [3]. The legs of this robot use a pantograph mechanism to magnify a semicircular trajectory that is produced from one rotational DOF as described above. This is done by tracing a predefined semicircular path as shown in Figure 1(b). This also shows that the stride length would be fixed. A separate DOF per leg is used for lifting the legs at point B in Figure 1(b).



(a) (b)

Figure 1: (a) THE MECHANICAL PLATFORM: STRIDER. (b) THE PANTOGRAPH LEG IS PIVOTED AT POINT **B**. THE TRAJECTORY AT POINT **A** IS MAGNIFIED 4 TIMES AT THE FOOT.

Although the method of changing gaits presented in this paper was designed for robots that use one DOF per leg to walk, it can still be adapted for use in other robots with higher DOF legs by maintaining a fixed stride length for each of their legs.

The method of changing between gait patterns will be shown using diagrams such as those originally used by Wilson [4]. The control system used for Strider will also be detailed.

PERIODIC GAITS

The two major classes of walking gaits are *periodic* and *non-periodic* gaits. This paper only concerns the changing between periodic gaits.

Two terms that are commonly used to describe the motions of a leg are the *retraction* and the *protraction*. The retraction is the process of moving a foot backwards (while it is on the ground) to propel the robot forward. The protraction is the process of lifting and moving a leg from the posterior (rear) to the anterior (front) of the robot for the next retraction.

Wilson's convention to describe gait patterns is described as follows. Figure 2 (adapted from [4]) shows a cockroach and a common insect walking pattern. This is actually a timing diagram of a stepping pattern. The numbers on the left side of the diagram (R3, R2 ... L2, L1) correspond to the leg numbering as shown in the picture of the cockroach. The black bars represent the protraction of a leg and have a fixed duration for any periodic gait. The dashed lines represent the retractions of a leg and have a variable time.

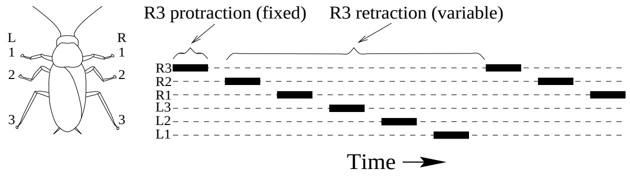


Figure 2: WILSON'S DIAGRAM OF A SLOW-WAVE GAIT.

The most common range of periodic gaits are the wave gaits [4]. A subset of these gaits is shown in Figure 3. Figures 3(a) and (c) are known as the *slow-wave* gait (protracting one leg at a time) and the *tripod* gait (protracting three legs at a time), respectively. At least three legs must be retracting on the ground at any time to maintain stability.

The sequence shown in Figure 3(a) can also be described using a convention from Hughes [5]. The sequence of protracting one leg at a time would be given as [R3, R2, R1, L3, L2, L1]. Figure 3(b) would be given as [(R3, L1), R2, (R1, L3), L2] and Figure 3(c) would be [(R3, R1, L2), (R2, L3, L1)].

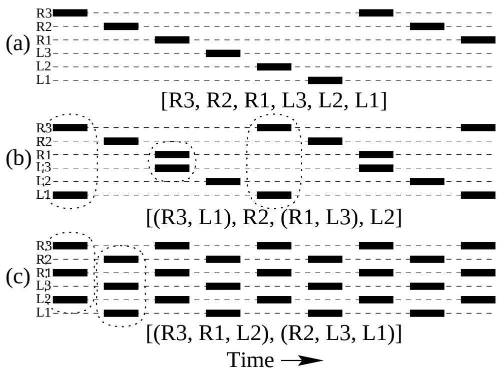


Figure 3: SOME EXAMPLES OF THE RANGE OF WAVE GAITS FOR SLOW WALKING (a), MEDIUM SPEED WALKING (b) AND FAST WALKING (c).

THE ROBOT CONTROL SYSTEM

Generating Periodic Gaits

The control system used for Strider was loosely based on Brooks' subsumption architecture [6]. Individual routines are represented by modules that are executed concurrently. The interaction between these modules define the behaviours that the robot will exhibit for a certain level of competence. The complete robot control system was designed with three levels of competence and is given in Figure 4.

The first level of competence for Strider's control system is used to servo-mechanise the rotational DOF of the legs. This is shown as the *Leg_Servo* module in Figure 4. This module actually contains other submodules which will not be covered in this discussion.

The *Leg_Servo* module receives an offset (or *delta*) value and will position a leg according to that value. It then outputs a flag to indicate that the position has been found. The delta values determine how far a foot should be positioned from the centre of the stride length. By incrementing the delta values, the legs would move backward to propel the robot forward. The delta positions of the legs are assumed to be initialised for a particular gait pattern prior to execution of the control system.

Each leg also has a predefined position that determines when a leg is positioned as far to the anterior as possible. This position is known as the Anterior Extreme Position (AEP). Likewise the furthermost posterior position of a leg is defined as the Posterior Extreme Position (PEP).

A very simple sequence generator can be added to the *Leg_Servo* module to make the robot walk using any valid periodic gait. This would be the second level of competence and is defined by three more modules in Figure 4 which are described below.

The *Increment* module will increment the current delta value of a leg after it receives an indication that the previous desired position has been found from the *Leg_Servo* module.

The *Protract* module monitors the delta values from the *Increment* module. When it finds that the leg's PEP has been reached, it will suppress (the s-node) the delta signal input to the *Leg_Servo* module and replace it with a signal to make the leg protract to the leg's AEP. The *Increment* module is then updated (or reset) with the AEP value for that leg. Each leg has it's own *Leg_Servo*, *Increment* and *Protract* modules.

One other (global) module is needed to synchronise the six legs and to complete the second level of competence. This module is called *All_Found*. The *All_Found* module will read the "found" output flag of each *Leg_Servo* module and will inhibit (the i-node) the next *Leg_Servo* delta positions (of every leg) until all of the current leg positions have been found. This will ensure that the leg positions maintain the same phase with respect to each other at all times.

Hence, by initialising the legs to a known configuration prior to the continual execution of the above system, for any particular periodic gait, the algorithm will continually update the robot's leg positions and the sequence of leg protractions will be maintained.

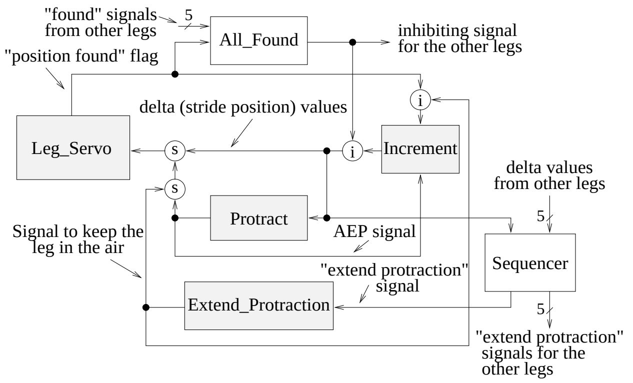


Figure 4: THE COMPLETE (GAIT CHANGING) SUBSUMPTION ARCHITECTURE BASED CONTROL SYSTEM. SHADED MODULES ARE DUPLICATED FOR EACH LEG.

Changing From One Gait to Another

Some hexapod control systems [7] [8] are able to change between gaits by changing the frequency of rhythmic oscillators used in their design. These systems require robot legs that have a variable stride length and hence, a variable retraction time.

Since robots that use only one DOF per leg have a fixed stride length, as mentioned above, gaits can only change from one to another by modifying the protraction time of the legs. That is, a leg that is lifted and being returned to the anterior of the robot must be delayed from reaching it's AEP until the leg needs to be placed down on the ground in order to synchronise it with another leg or legs. In Figure 2 this would be shown as an extension of the length of the black bars.

To change from one gait to another requires knowing which legs need their protraction extended and which legs they need to be synchronised with. Once these have been determined the data can be stored in a table to be read by the control system. It is important however, to ensure that when one protracting leg is being delayed, that one of the ipsilateral legs (a leg that is directly next to and on the same side) is not protracting also. This would cause the robot to become unstable and fall over.

Two more modules in Figure 4 are added to the control system to allow the robot to change from one gait to another. These modules, *Extend_Protraction* and *Sequencer*, constitute a third layer in the control system that subsumes the role of the first two layers.

The *Sequencer* module reads the delta values for each leg and signals appropriate *Extend_Protraction* modules (predetermined in a table) to extend the protraction of those legs.

The *Extend_Protraction* module keeps a leg off the ground, and hence extends the protraction of the leg by suppressing the signal from the *Protract* module and replacing it with a delta position value to keep the leg in the air. The "found" flag is inhibited by this signal to prevent the delta value from being incremented.

The signals input to the *Extend_Protraction* modules must eventually be removed by the *Sequencer* module in order to place the legs down (and start retracting) at the same time as those legs that they are to be synchronised with. The legs to be synchronised with must be predetermined in a table, as mentioned above.

The examples below demonstrate how the control system would extend the protraction of certain legs in order to change the gait and hence the walking speed of the robot.

EXAMPLES OF CHANGING GAITS

Increasing Speed from a Slow-Wave Gait

The initial slow-wave gait is shown in Figure 5(a). In order to increase the walking speed such that the robot uses the gait shown in Figure 5(c), the protraction of the legs L1 and R1 must be extended. These legs must finish protracting and then start retracting at the same time that legs R2 and L2 start retracting, respectively, in order to be synchronised with them.

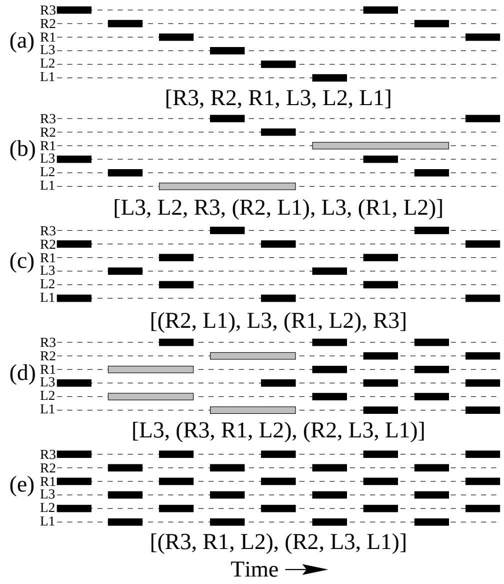


Figure 5: INCREASING SPEED: CHANGING FROM A SLOW-WAVE GAIT (a), VIA (b) TO A MEDIUM SPEED GAIT (c), THEN VIA (d) TO A TRIPOD GAIT (e).

This can best be explained by observing the changing gait shown in Figure 5(b). Here we can see that by extending the protraction of L1 (the shaded bar), that this lifted leg will not interfere with any ipsilateral leg (L3 or L2) since they are both retracting. That is, L3 and L2 are on the ground holding the robot up. Leg L1 is then placed down at the same time as leg R2. The same is done for leg R1.

When the robot continues walking, the previous duration that was originally used to protract legs L1 and R1 can be removed. Therefore, the retraction time for every leg will reduce by two protraction time lengths since we no longer need to wait for the end of those protractions. Hence the robot will be walking faster using the medium speed gait in Figure 5(c).

Now, for changing from the medium walking gait in Figure 5(c) to the tripod gait in Figure 5(e), the protraction of two legs that are protracting simultaneously need to be extended and synchronised with a third leg. In this example, the protraction of legs R1 and L2 are extended and synchronised with leg R3 in the same way as before. Then, R2 and L1 are synchronised with L3. Again the retraction time is reduced causing the robot to walk faster. The new walking sequence will now be the tripod gait.

The changing gaits shown in Figure 5 have been tested on Strider. The robot successfully changed it's speed from a slow walk, to a medium speed and finally to a fast tripod gait.

Decreasing Speed

In order to decrease the robot's speed the protraction of some legs again need to be extended. However, in this case, when the legs end their protraction they do not get synchronised with any other leg whose protraction has also ended. Instead, the aim is to extend the retraction of the currently standing legs. This can be done by allowing the *Sequencer* module in Figure 4 to wait for several stride (delta) increments until a single protraction duration has passed and then start retracting the leg. This method is shown in Figure 6.

As can be seen in Figure 6(b), the protraction of legs R1 and L2 are first extended. The retraction time of the legs R2, L3 and L1 are extended (the dotted lines) which causes the robot's speed to reduce. Leg R3 is left unchanged. The protraction of legs R2 and L1 are then extended while the retraction time of legs R3, R1 and L2 are extended to reduce the robot's speed to that of the medium speed gait in Figure 6(c). The same method is again used to change from (c) to (e). Here, the protraction of L1 is first extended, followed by R1.

The changing gaits shown in Figure 6 have been tested on Strider. The robot successfully changed it's speed from a fast tripod gait to a slow single-step gait.

CONCLUSION

A method of changing between some walking patterns for a hexapod robot has been presented. The method was used to change the gait and hence the walking speed of a robot that uses only one degree-of-freedom per leg to walk. However, the method can still be used for other hexapod robots that have two or more degrees-of-freedom per leg.

A subsumption architecture-based control system was described. Examples showed how to change from a slow-wave gait up to a tripod gait. This showed that the walking speed can be increased. The method of decreasing the walking speed was also shown. The changing gaits were tested on a hexapod robot and they allowed it to successfully change it's walking speed.

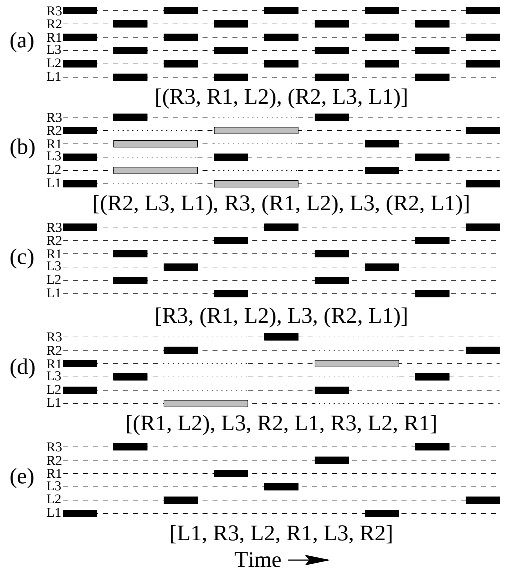


Figure 6: DECREASING SPEED FROM A TRIPOD GAIT (a), VIA (b) TO A MEDIUM SPEED GAIT (c), THEN VIA (d) TO A SLOW GAIT (e).

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