CONTROL OF WALKING BY CENTRAL PATTERN GENERATORS

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Abstract. *Research into legged robots predates the discovery of the neural basis of rhythmical motion in animals by several decades. As a result almost no research in legged robotics has ever been based on this, and indeed most is still derived from personal insight or previous biological theories which are now known to be flawed. One group which has used these ideas to design a control structure for a robot is Taga and his colleagues, who made a crude simulation of a planar biped controlled by neural oscillators. In this paper we replicate and extend Taga's work, correcting flaws in the original model which made it extremely mechanically implausible. Disappointingly, it was found that the original model was only stable in a very limited range of conditions. However, making the model more realistic has improved this considerably, and the authors are now investigating further similar biologically inspired control structures.*

Key Words. Simulation, Central Pattern Generators, Robotics

1. BACKGROUND

Most recent work on robotic walking has fallen into one of two groups: either it has involved reflex chains where actions trigger each other in loops, for instance recent work by Brooks (Brooks, 1986; and onwards) on statically stable walking, or a more high level modelling approach such as that of Raibert (Raibert, 1988; and others) on dynamically stable locomotion, where algorithms in the central processor calculate required forces for the desired action. The former is an old idea, based in biological theories of the 1930's and 40's (*e.g.* (Gray *et al.*, 1938)), and the latter is more recent, based on evidence of centralised control (for a summary, see (Delcomyn, 1980)). However in neurophysiology both of these ideas have now given way to a middle ground, where motor acts are controlled by an intermediate level neural network which generates a rhythm and which receives both simple high level control signals and sensory feedback.

In vertebrates (Grillner, 1983) the evidence points towards control mechanisms in the spinal chord which create the essential features of the rhythmical motor pattern whilst receiving large amounts of proprioceptive feedback to allow adaptation to actual conditions as well as simple high level control signals from the brain (for instance to determine speed). This allows a stable rhythm to be built up as a kind of global limit cycle, and it is this which is lacking in both of the previous methods. These controllers are called Central Pattern Generators (CPGs). Only recently has the first work been done which has produced data on their detailed structure in vertebrates (Grillner *et al.*, 1991).

Taga's Work

At the same time, work was being done on dynamically stable walking controlled by neural networks (Taga *et al.*, 1991). This was using a crude simulation of a biped in two dimensions and a simple network of neural oscillators with a single non-specific high level input to control the speed. There was one neural oscillator controlling each joint with all of the neurons using sensory feedback from the "muscles" as crucial inputs to correct timing. The control structure is shown in figure 1.

Although he made no effort to base the oscillators themselves on any biologically plausible system, the overall design was based on Central Pattern Generators, and his results showed that at least in this simple model they were suitable as a control mechanism. The legs could walk and run on flat ground and climb up gentle slopes, changing between different gaits automatically; the coupled system had a robustly stable limit cycle which was largely predetermined by the dynamics of the neural network, but which was adjusted by the speed input and the sensory feedback from the legs.

It is important to note that these adjustments occurred simply as a result of the operation of the

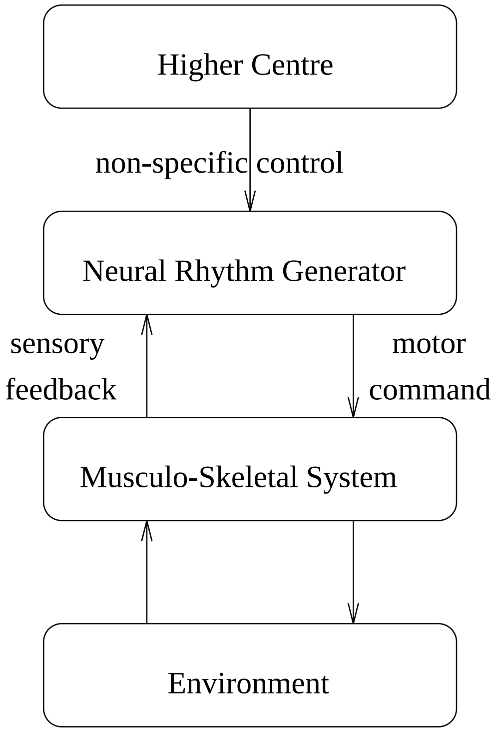

Figure 1 *Control structure for legs*

neural network, and thus there was no modelling or extra calculation involved. This means that the system is not computationally intensive, and there should be no problems in running it in real time on an actual robot.

2. EXPERIMENTS

Taga claims that his system is "stable to mechanical perturbations and to environmental changes". An reimplementation of the simulation exactly as it is described in Taga (*ibid.*) showed there to be several weaknesses in this claim. The most significant was that the simulation is very susceptible to falling over when it changes speed, especially when it starts to run; another was that it was totally incapable of walking on uneven ground.

Examination of the dynamics given in Taga (*ibid.*) revealed that the ground was modelled extremely implausibly, causing the legs to fall over whenever they brushed it. This was because it acted like a springy rubber mat which glued the robot's foot to the position it first touched the ground until the foot was lifted again.

Dynamics algorithms

Another problem was in the dynamics algorithm which modelled the legs. This was a very simple open form Newton-Euler technique, based on the idea that the legs were made up of 5 interacting rigid bodies (the hip, thighs and shins) and his equations described them in these terms (see figure 2). There were 14 differential equations relating acceleration to known external and unknown internal reaction forces, and 8 constraint equations to keep the legs intact which were differentiated twice to be in terms of the coordinate accelerations. Initially these 8 unknown reaction forces were eliminated from the differential equations to give closed form equations for the accelerations of the 14 leg coordinates. The simulation was then run using these equations.

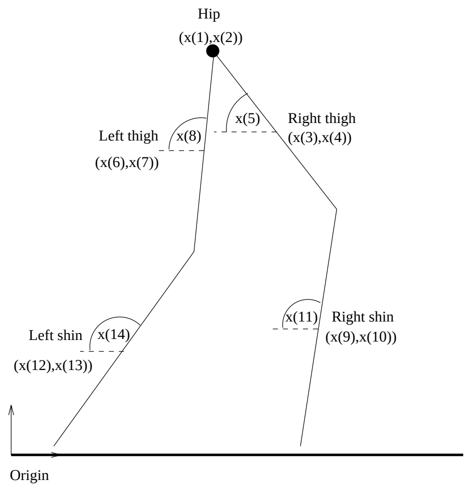

Figure 2 *Original design of legs*

Unfortunately, as well as being exceedingly slow, this method allowed allowed errors to build very easily as a lot of redundant information was being calculated: the legs only had 6 degrees of freedom, but their position was being calculated in terms of 14 coordinates. On paper this made no difference, but as the constraint equations which should have kept the segments together were only constraining the *accelerations*, small errors allowed the legs to come slowly apart at the joints. The easiest solution to this was to increase the accuracy of the simulation, but as it was already taking a week to do a simulation run, this was deemed impractical.

Instead, the constraint equations were used to eliminate the 8 redundant coordinates completely, leaving only the position of the hip, and the angles of the four other segments (x_1, x_2, x_5, x_8, x_{11} and x_{14} on the diagram). This completely stopped this source of errors, and, by reducing the number of variables being integrated, speeded up the simulation enormously.

Regrettably it made the differential equations governing the accelerations completely opaque (although they had already been quite difficult to understand because of eliminating the reaction forces), and any changes which were made later had to be done on the original equations, and the (extremely laborious) eliminations had to be done again.

As a result, it was decided to investigate an iterative method which would not require this compilation. The method chosen was the Composite Rigid Body algorithm (Walker and Orin, 1982; Featherstone, 1984). This allowed the model to be rewritten in a simplified form, with each segment having its own local coordinate system (see figure 3). It also allowed the model to be represented in three dimensions, although the current model still only moves in two. Nonetheless, this will be very useful later when the model does become three dimensional, as it will mean there will be no need to completely rewrite the dynamics a second time.

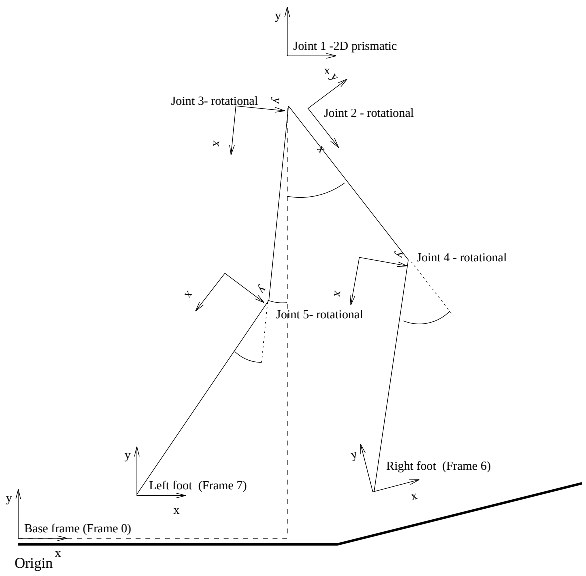

Figure 3 *Composite Rigid Body model of legs*

Ground redesign

After this had been sorted out, we decided to redesign the model of the ground. In contact between a point and a surface, there is some deformation, particularly normal to the plane of the surface. However along the plane, although there is some deformation (shear), far more significant is Coulombic friction, and this was not accounted for at all in Taga's model.

Coulombic (or slip-stick) friction was therefore implemented parallel to the ground. This is straightforward when the foot is slipping, but when it is stuck it is necessary to work out the force required to oppose the acceleration, and this is calculated from the instantaneous inertia of the body; this has been achieved, but at a high computational cost.

There was also a problem that the feet sink too far into the floor when walking (usually about 5cm). This has been temporarily solved by increasing the coefficient of restitution of the ground, but this makes the integration a much stiffer problem, and the simulation algorithm is not designed to cope with this. Other solutions are available, particularily allowing impulses in the model, but this has been left for the future; as things stand, the increased stiffness of the equations is just increasing the time the simulation takes.

3. RESULTS

The results taken were intended to test the simulation on a wide variety of different slopes and surfaces to see at which speeds (if any) it could walk on them. Each test was run over 20s of simulated time from the same starting position, and there were four possible results:

- S for a stable walking pattern which completed the run
- U for an unstable walking pattern which completed the run
- F if the legs fell over forwards
- B if the legs fell over backwards

The tests were run three times, once on the exact original design by Taga, then on the same design with stiffer ground, and finally on the new model with the ground reworked to allow Coulombic friction.

With the first two designs, the tests were intended to find out at what speeds the legs could walk on slopes varying from -10% to $+10\%$, and tables were drawn of the results to show the areas of stability.

With Coulombic friction implemented on the ground, the coefficient of friction was also allowed to vary, and so the surface is described in terms of that and the angle of the slope, and a table has been drawn similar to the previous ones, but showing the range of values of μ (the coefficient of friction) over which the legs are stable.

Original design

Figures 4 and 5 show the stability of different walking speeds on various slopes with the original model, and the same model with stiffer ground respectively.

As you can see the first set of results is extremely poor — there is only a very limited area of stability, and the legs are completely incapable of dealing with steep slopes, because they trip up,

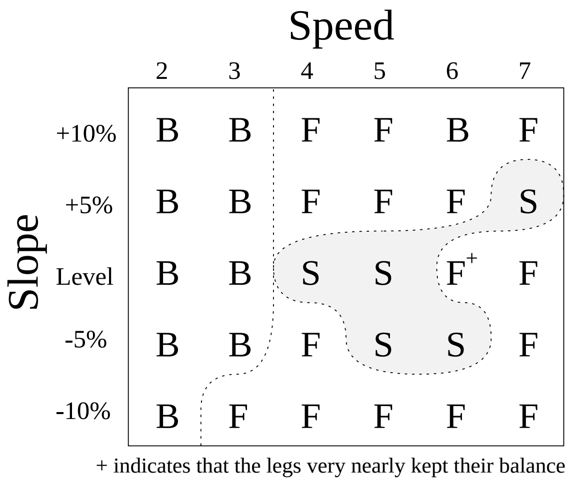

Figure 4 *Results of testing of Taga's original model*

or walking too slowly, as the feet sink too far into the ground and they can't be lifted back out. It is possible that if there had been specific starting positions for each run, more of the runs could have shown some stability, but that would only have been evidence of local stabilities which could probably have been disrupted by unevennesses in the ground. In any case the starting position chosen was taken from Taga's paper and was a very sensible one: a stationary stance with one leg slightly ahead of the other for stability.

The main failing was that the legs tripped up very easily (nearly every case of the legs falling over forward and some where they fell over backwards were a result of a foot catching the ground while swinging forward). This was remedied in the second set of tests by increasing the stiffness of the floor.

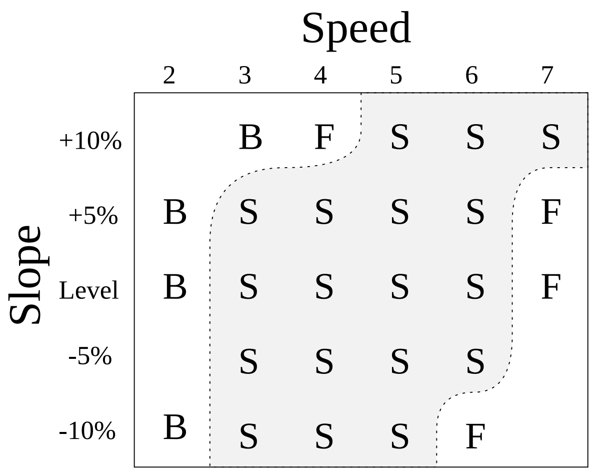

Figure 5 *Results of testing of Taga's model with stiffer ground*

The second set of results (Figure 5) are very good, with the feet very rarely tripping over since there is that extra bit of ground clearance. Indeed they are exactly the kind of results we would like to see in a walking robot — any slope can be tackled except steep uphill going too slowly, or steep downhill going too fast, and there is a good range of speeds the walking is stable over for any given slope. However explanations can be given for why this is so which have nothing to do with the stability of the system:

- With the stiffer ground, the feet do not slip when they are in contact, so when going up or down steep slopes the situation is much easier to control than it would otherwise be.
- Since the ankles are treated as joints and generate torques when in contact with the ground, they help lever the legs up hills when otherwise they would fall over backwards.

The first of these two problems has been tackled by introducing Coulombic friction: full results of this can be seen in the next section. Unfortunately the second problem requires a complete redesign of the neural oscillator and so has been left for a later date (see next section).

Coulombic friction

Figure 6 shows the range of values of μ (the coefficient of friction) over which the walking is stable for different speeds and slopes.

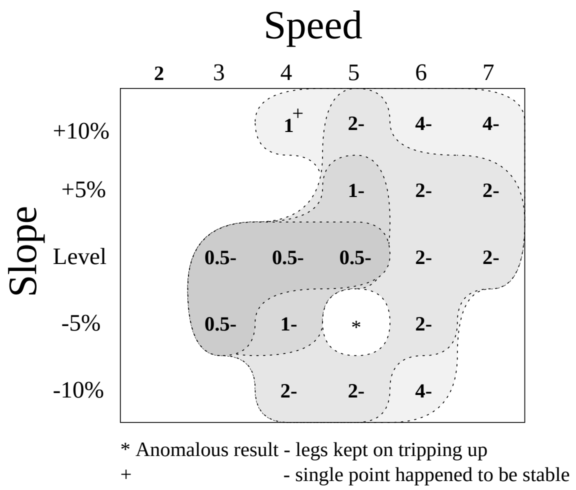

Figure 6 *Range of values of μ over which Coulombic friction model is stable*

The results are not as impressive as those for the stiffer original ground, and there are a couple of small anomalies, but they are still satisfying because they have a fairly broad range of stability and in several of them the legs manage to control a considerable amount of sliding. In fact, the results of the previous method are very similar to the Coulombic friction model with very high friction. Unfortunately none of the new model manage to walk on the most icy surface ($\mu = 0.25$), but a couple do survive for over fifteen seconds before they finally slip up (see figure 7 for example). The results of these runs still make sense, just as those for the previous model did, following intuitive rules:

- The steeper hills cannot be climbed if you are going too slowly, and cannot be descended if you are going too fast.
- The lower the coefficient of friction, the slower you have to go to avoid slipping up, and conversely the higher the coefficient of friction, the faster you can go and still keep your grip.

The notable exceptions to these rules are the two anomalies shown in the table; we could find no definite explanation for either of them — in the case of the legs going downhill, there was a problem with just one speed which couldn't walk on that slope at all, whereas the others had no problems, and that leads me to believe there may be some resonance effect building up, but there was no time to investigate this. In the other case going uphill, I think it was just chance that the legs happened to be stable under those particular conditions.

Overall they are a good set of results and the system shows stability over a reasonable range of different surfaces, with the caveat that there are still torques being generated in the ankles which help on uphill slopes.

4. CONCLUSION

As we have said before the motivation for this project was to see whether it was feasible to implement Central Pattern Generators as an intermediate level control system for a walking robot. We have taken the work of Taga and his colleagues in (Taga *et al.*, 1991), which showed that there was potential in the idea, and improved upon it.

We were pleased to find that adding more mechanical plausibility to the model actually improved its ability to cope with different surfaces, and this gives us cause to hope that the method is sound at least for simple systems. Of course we know that a similar but far more complex method is used in animals such as vertebrates to control locomotion, but it is quite likely that too many simplifying assumptions have been made in designing these neural oscillators for comparisons to be drawn.

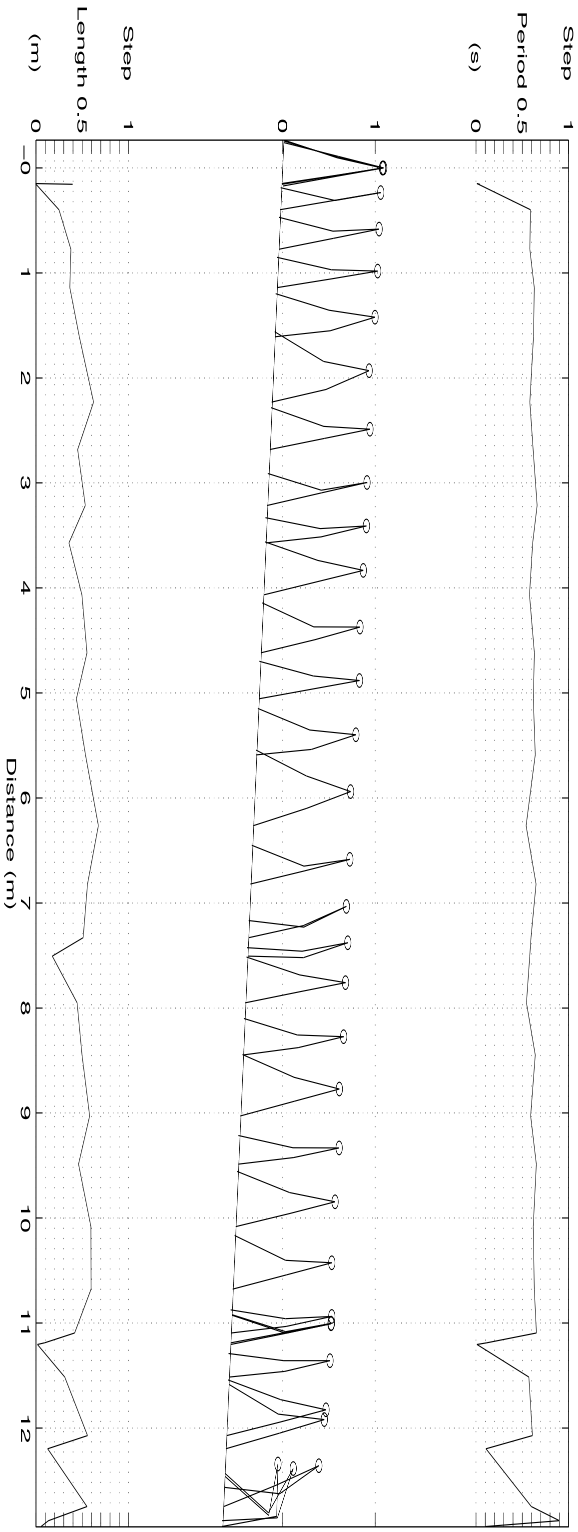

Figure 7 *With the Coulombic friction model the feet can slide, making balancing considerably more difficult.*

Quite apart from the results we have collected, this project has produced something far more important by reworking the model to use the Composite Rigid Body dynamics algorithm. This means that the model is much more clearly defined, and future changes to it can be carried out far more straightforwardly.

Overall, this project has only been a small beginning in the work of testing the feasibility of Central Pattern Generators as a control strategy. Indeed, very little has actually been done on the control side in the end, as the simulator itself required too much attention; however, the work on the dynamics algorithms has been very productive, opening the way for the control side to be investigated much more easily.

5. FURTHER WORK

At the present time, there is only one more alteration that we would like to make to the simulation and dynamics algorithms, and that is to redesign them to cope with impulses. After that, we think that attention can rightly turn to the model itself. The model divides into two broad areas: the control structure and the musculo-skeletal system. Of these we think that the control structure should be considered first, and we propose scrapping the entire Neural Rhythm Generator handed down from Taga, and starting again from scratch in order to understand how they can be made to work. Once an understanding has been gained of this, the model should be expanded to three dimensions, and then the control structure should again be built up around it.

Impulses and Friction

The only major shortcoming currently seen in the simulator (as opposed to the model) is that forces orders of magnitude bigger than any others found in the simulation occur in two places: in the knees, to stop them bending the wrong way, and in the feet, to stop them sinking into the ground. In both of these cases the forces are intended to stop further movement in a particular direction, but, although they have some success in this, they increase the stiffness of the problem considerably. An alternative solution, which has been used effectively in other simulators (*e.g.* (Featherstone, 1984)), is to allow contact to generate impulses to halt movement, and then have normal reaction forces to keep relative motion at zero until contact is broken. These impulses and normal reaction forces would be used to replace the current elastic deformation and viscous friction model of the ground, and the similar part of the model of the knee.

This would be quite a large piece of work, and will require a search for a suitable simulation algorithm, but most of the adjustments needed for the dynamics algorithm are available from Featherstone (*ibid.*).

Central Pattern Generators

The Neural Rhythm Generator used throughout this project has caused serious problems because it was presented as a finished product with no justification for its design, and none was found in early attempts before that line of attack was abandoned in favour of other more productive ones. As well as a general lack of justification there were serious specific problems, such as the fact that the ankles were treated as joints despite the lack of feet in the model, and consequently torques were generated in them which could not be justified, causing ridiculous positions of stability such as that shown in figure 8 where the centre of gravity is far behind the only point of support, but the legs were kept from falling over by this ankle torque. Indeed in this instance, after balancing there for a while, the legs actually fell over forwards.

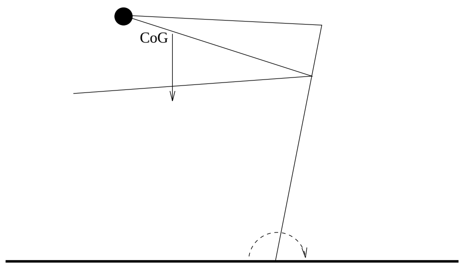

Figure 8 A stable position for the legs using Taga's model

As a result we propose completely scrapping the neural network and starting again with the aim of developing a method for automatically designing Central Pattern Generators to control mechanical systems. Obviously this can only be a long term aim, but one possible method I propose is to develop a Genetic Algorithm which has Central Pattern Generators as phenotypes, and whose fitness function is an adaption of the simulator which returns some assessment of how well the model walks. The Genetic Algorithm would then be able to evolve suitable CPGs for different models.

Clearly this is fairly speculative and may prove impractical, but similar work in generating control systems and indeed entire creatures has been done very recently (Sims, 1994). Furthermore, realistically it is essential that if CPGs are to be useful as a control mechanism some method must be developed for designing them, so if this approach does not work some other method will have to be found.

Three Dimensions

One of the long term goals here is to develop a walking robot, and, to this end, the current model must be upgraded to a full three dimensions. However, it is important not to put the cart before the horse; as things stand we have a fair understanding of how the mechanics of the model work, and it would not be impossible to go ahead and add a third dimension to it. However, as we have already said, we have very little understanding of the control system, and, without trying to understand this in the relatively simple case of a two dimensional model, there is no hope of succeeding in the enormously more complex three dimensional case.

Consequently, though a three dimensional model is an aim, there should be no great urgency in attempting to build one, as the control system should be the focus of attention for some time to come.

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