Control of Walking Machines With Artificial Reflexes

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Abstract

This paper describes the augmentation of our concept for the locomotion control of multi-legged walking machines. The concept is based on a neural control with artificial reflexes to react on sensor input. It is improved with the help of new sensorics as well as an internal ground map, build up with sensor information. Parts of the general concept together with the used sensorics are introduced. The ground map and its generation as well as the collaboration between the different reflexes are shown. The presented methods are applied to the six-legged TARRY I and TARRY II, but they are applicable to many other types of walking machines.

1. Introduction

The aim of the TARRY project is to realize autonomous walking in unknown and rough terrain. TARRY I and TARRY II, the machines we use to verify our software in the real world, were designed and manufactured in 1992[1] and 1999[2]. They are modeled according to the walking stick insect *carausius morosus*, where TARRY II has undergone many subtle changes that were derived from our experience with its predecessor TARRY I.

Both TARRY robots have six legs with three rotational joints each. The joints are modeled with servomotors used in airplane modeling normally. The whole structure is built to be as light as possible to allow a relatively high payload or a larger area of feasible motions. The machines are equipped with several sensors that are discussed below. Most important are to contact sensors in the feet to detect ground contact and the current measurement in the hip servos the recognize leg collisions.

To enable locomotion in different kinds of terrain we use a combination of several techniques. As a basis for walking in standard gaits we generate and optimize a set of walking patterns. These patterns are based on the machine's kinematics and a set of sixteen walking parameters (see table 1). Some of them are obvious as velocities in x- and y- direction and angular velocity around the z-axis. They are supplemented by values for roll and pitch angle as well as superimposed oscillations etc. These parameters together with the kinematical model of the machine are fed into the software library WALKINGLIB[3] creating the needed walking patterns. The WALKINGLIB creates the foot trajectories in cartesian coordinates or derives the joint angles via inverse kinematics.

These generated walking patterns are used to train a set of six neural networks (see figure 3), one for each leg, with the basic gaits. Their input values are also tied to a pacemaker to secure synchronization of the legs. The networks are feed forward networks that are trained by standard backpropagation algorithms[4].

Figure 1: Walking stick insect *carausius morosus*

Figure 2: Walking machine TARRY II in motion

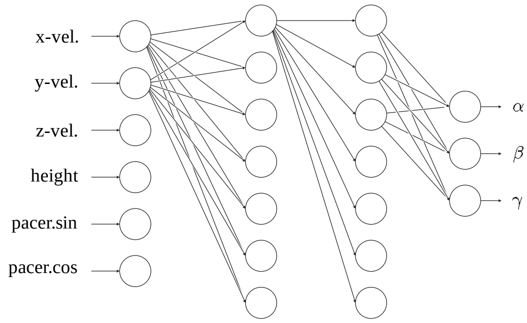


Figure 3: Neural Network

Table 1: Parameters of gait generation

Name	Meaning
XDot	Velocity in x-direction
YDot	Velocity in y-direction
OmegaZ	Angular velocity around z-axis
StepWidth[ ]	Step width per pair of legs
StepHeight	Step heigth
StepDuration	Step duration
RollAngle	Angle of rotation around y-axis
PitchAngle	Angle of rotation around x-axis
DutyFactor	Duty factor
BodyHeight	Height of body above ground
StanceCenter[ ]	Stance center per pair of legs
Phase[ ]	Phase difference per pair of legs
AmplitudeX	Ampl. superimp. osc. (x-dir.)
PhaseX	Phase superimp. osc. (x-dir.)
AmplitudeY	Ampl. superimp. osc. (y-dir.)
PhaseY	Phase superimp. osc. (y-dir.)

To train the neural networks a simplified set of input parameters together with the joint angles of the respective leg as outputs are used. Each of the six networks has six input neurons that are velocity in x- and y-direction, angular velocity around the z-axis as well as the body height for the individual leg. As already mentioned a pacemaker, giving two additional inputs, synchronizes all networks.

All sets of walking patterns as they have been created are only suitable for walking on even terrain. None of them is able to facilitate walking in rough terrain in the original combination.

To provide useful propulsion in rough terrain the given trajectories have to be adapted to meet the real environment. To do this, a set of sensors is used to observe the state and the properties of certain elements of the walking machine and to react in convenient ways.

These reactions, also called reflexes in the following, are able to initiate an adaptation of the input values of each neural network. On the one hand they can cause local reactions, which provide only changes to one leg. This method is used for small corrections. On the other hand they are able to manipulate the input values of all legs. This behavior is called a global action and is taken for large corrections or changes that demand cooperation between all legs, such as changes of direction of locomotion or the orientation.

With these coded reflexes the machine is able to climb or avoid obstacles, to walk over bumps and small holes as well as balancing slopes just by rearranging the input of the networks trained with basic gaits.

2. Sensorics

The robots have several types of sensors. As already mentioned, the most important part are the ground contact sensors mounted in each foot. They enable the machine to detect whether a foot has ground contact or not. They are simple switches just delivering binary information. Another important element, needed for proper locomotion is the measurement of the servo motors' current to detect collisions with obstacles. These sensors deliver sufficient information to initiate the so called Levator-Reflex, also observed at the walking stick insect. In addition the servomotors are able to measure their own angular position.

These two sets of main sensors are completed by several other input sources. To get the information about the load the middle segment of each leg has been equipped with four strain measurement gauges. This enables the robot to improve the ability to detect obstacles that do not come up in the longitudinal axis of the walking machine. To give the machine the ability to level its own orientation as well as to enable the internal model to identify its relation to the environment an inclinometer with two axes has been installed.

Most of the data the sensors deliver is smoothed and filtered to get reasonable information, suited for further processing.

3. Artificial reflexes

To meet the current environmental conditions several different modules are working to propel the machine in a useful way. This cooperation is done by reflexes of different levels where some of them have to rely on the information others have gathered or even have to delegate some tasks to them.

The most important of the implemented reflexes are the reflexes to overcome obstacles and to secure proper standing. They are followed by a reflex to correct the

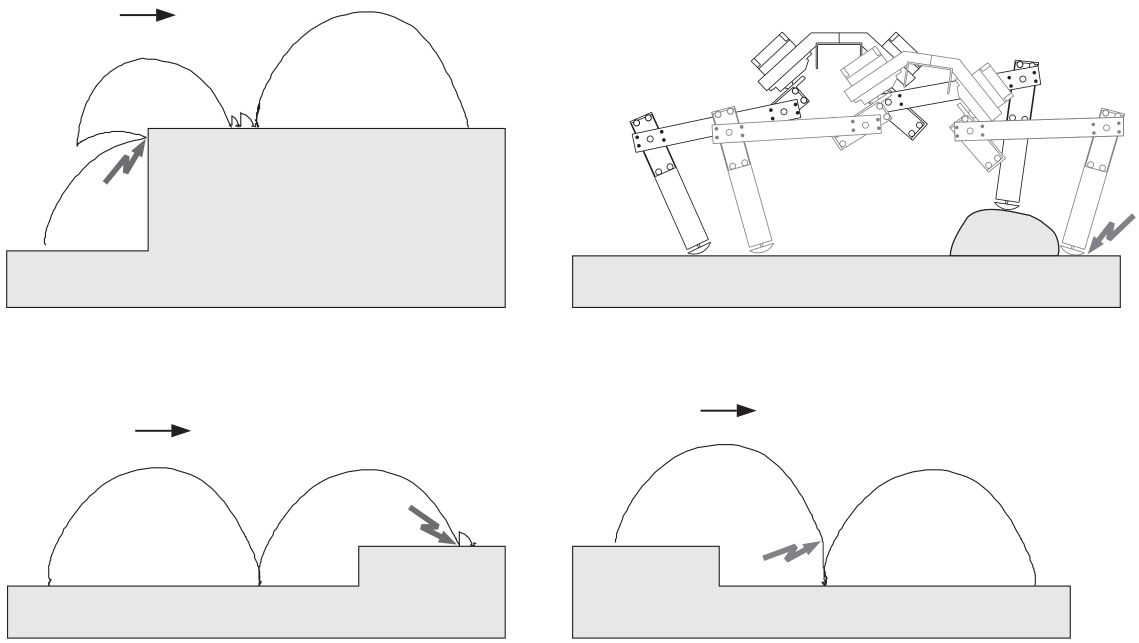


Figure 4: Schematic view of some reflex actions

machine after slipping from an obstacle, to lift or lower the body to a reasonable body height and body orientation. The lowest level is formed by reflex actions to navigate the machine, such as the ultrasonic module. An ultrasonic sensor scans the environment in front of the machine for large obstacles. If an obstacle in the current walking direction is detected the course is changed to pass by. The lower levels are only able to change values if they do not interfere with other reactions as they are supposed not to disturb critical events that demand instant reaction.

3.1. Securing ground contact

To secure proper ground contact the former pattern based approach[1] has been replaced by a neural network based method. Although the simple usage of the pattern-based approach is appealing it has two major drawbacks. It just works with selected gaits just as tripod gait and it does not take the inaccuracies and elasticity of the machine into account, as it just compares the current stance pattern with two fixed stance patterns.

The chosen neural approach relies on the real machine as model for itself. The machine walks on a plane with its basic gaits and the arising stance patterns combined with the belonging pacemaker information are recorded. This information is taken to train a neural network with the pacemaker as input and the stance pattern as output values. This method has the additional advantage, that leaps in the pattern on hitting the ground get smoothed in the output. During normal walk the current stance pattern is compared with the response of the network to the current pacemaker position, creating a correction if some values are not met.

3.2. Leveling the machine

To be able to fully level the machine, a sensor to detect the inclination of the robot has to be used. Before this sensor had been mounted the machine tried to achieve horizontal alignment by using information about the leg angles as well as the assumption of a plane ground. This method has been comparatively successful although it was not able to detect slopes e.g.

With the addition of the Analog Devices ADXL 202 accelerometer[5] the machine gained the ability to measure its angle in relation to the gravitation. The strategy to level out the measured angle relies partly on the other implemented reflex actions. To put the robot into horizontal orientation the geometric characteristics of the machine are used. Although the WALKINGLIB provides some parameters for the creation of walking patterns with roll and pitch angles (see table 1) another approach has been taken. To use the roll and pitch angles inside the neural control it would have been necessary to extend the number of input neurons. To avoid this and keep the simple structure of the neural control a pure geometrical approach has been taken to change the inclination of the robot. In principle the geometric properties of the machine are changing periodically during a walking cycle, as shown in figure 5. Under normal conditions this effect only occurs in longitudinal direction, as the relative contact points change during the support phase of the feet, but depending on the situation even the traversal geometry could change.

The main part of the control strategy to align the machine to a horizontal state is based on a simple p-control changing the height of the body for the individual legs. With values that have been determined experimentally before, raise and lower commands for each leg are generated. Due to the geometric problems described above, this can cause a leg to take off the ground. The reflex to level out the machine does not take this into account but instead relies on a collaborating reflex. As a leg looses contact the respective reflex takes place automatically. It forces the leg lifting too early, to move back towards the ground, thus guaranteeing a secure standing.

The necessary parameters as the amplification of the controller have been derived experimentally to secure fast as well as stable control of the inclination. The control mechanism is able to deal with small changes as they occur in normal walking as well as with seesaw like situations.

If large changes in inclination occur over a short period of time the machine stops walking to adjust to the new situation. By this mechanism it is also possible to deal with the large changes that occur if the machine has climbed an obstacle and slips down.

4. Ground map

The coordination of the walking stick insect *carausius morosus* is built in an extremely decentralized

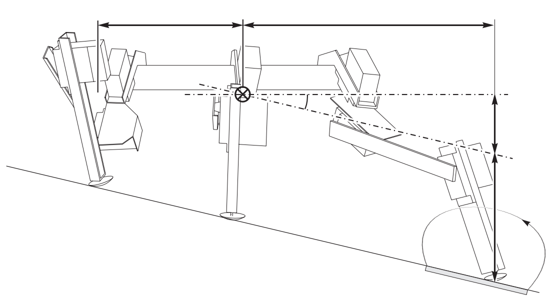


Figure 5: Geometric proportions of TARRY II

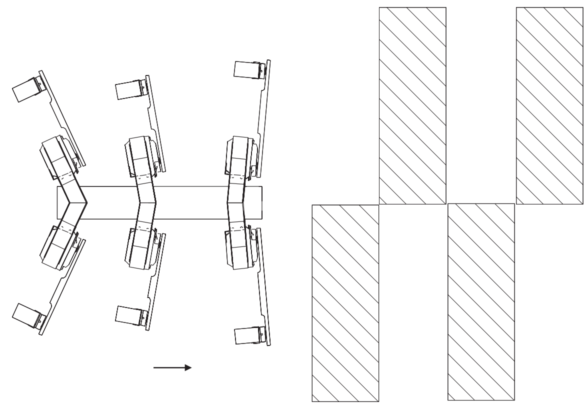


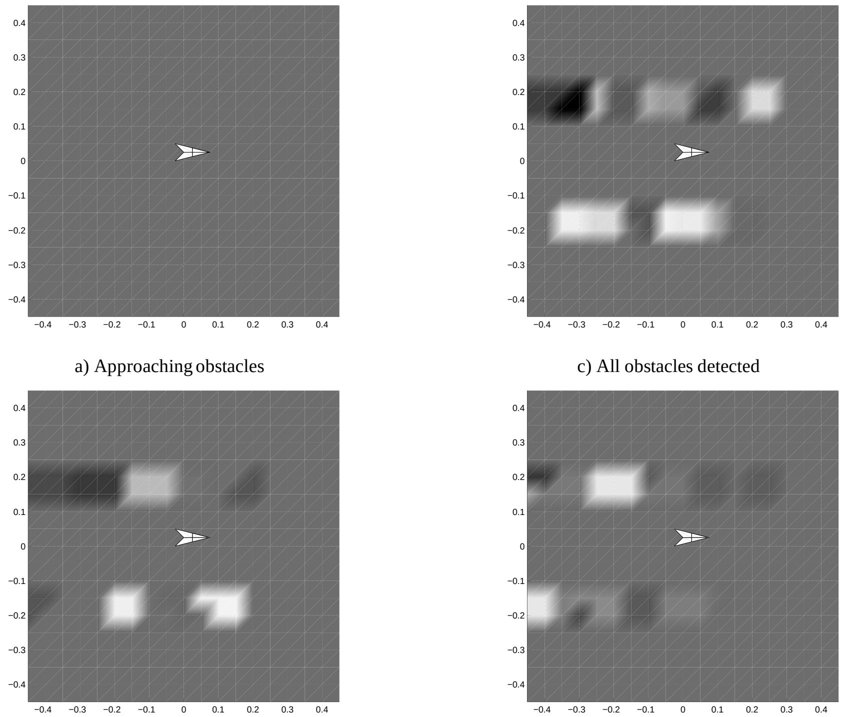
Figure 6: Alternating beams as obstacles

manner[6], working with stimulating and repressive excitements. The system does not seem to affect the feet height of lateral neighboring legs. Due to this the subsequent legs also collide with an obstacle, even if it has been hit before.

This was the same with the walking machine TARRY. But as we use a more centralized approach we are able to create a global repository for information the machine gathers. To take the inaccuracy of the robot and its relatively poor repetitive accuracy into account, we just memorize the small area directly below the machine enlarged by a reasonable border.

Due to the machines knowledge about its current angular servo positions and the feet with ground contact it is able to determine the position of the feet in a body fixed frame. Together with the orientation of the body the information about the relative height of the ground can be achieved. With this information a local map is constructed. As the machine itself has no idea about its geometry it is not able to compute the cartesian position of the feet with the known joint angles without help. To get this information, the WALKINGLIB provides an internal model for the machine that is updated permanently. The current joint and inclination angles are given and the model calculates the feet positions that can be used to update the internal map. The mapped area is moving with the machine. With an enlargement of these foot contact points to areas the machine is able to adapt the height of the successional feet before a collision takes place. As a result the machine bears recently detected obstacles in mind to pass by fluently and without interruption after the first collision has taken place.

An example for an obstacle configuration is given in figure 6. The machine approaches a set of alternating obstacles. At this point the map looks like in figure 7a. As there has been no disturbance the map con-



a) Approaching obstacles

c) All obstacles detected

b) Between the obstacles

d) Crossing completed

Figure 7: Graphical representation of an evolving ground map

sist just of one level, indicated by the plain gray color. In fig. 7b the machine has taken the first three obstacles, that are now marked as light spots, denoting the elevated ground. Due to inaccuracies the dark trail in the upper left area has been created. As reaction to lost ground contact detected by the respective reflex the last left leg had to be lowered to reconstitute the contact. In fig. 7c TARRY II has passed all obstacles with at least one leg as they are marked in the map. Some more areas have been marked as lower-leveled, as described above. Finally in fig. 7d all obstacles have been passed completely. The inexactness of the detected ground begins to converge to the real, even ground, now.

As one can see in the video belonging to this example[7], the machine has been able to pass this configuration much faster and without unnecessary interruptions.

5. Conclusions

The control strategy of the TARRY walking machines utilizes a set of basic gaits learned beforehand to achieve movement. These basic gaits are created with a kinematical model and a set of parameters with the help of the WALKINGLIB. They are adapted due to sensor input by different kinds of reflex actions to create a proper leg motion. The different reflex actions are initiated by different kinds of sensor signals. Some of them work completely local with their own data, others rely on an internal model of the machine or on data that has been stored in a central repository. With these methods the machines are able to walk through different kinds of rough terrain. They are able to memorize the explored environment for a short time and to react according to this knowledge. In addition they are able to adapt their orientation according to the information of the inclinometer.

In future applications the robot should be able to adapt some of the internal parameters online as a reaction on recent explorations.

Acknowledgments

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