



SIMON FRASER UNIVERSITY
THINKING OF THE WORLD



ÉCOLE POLYTECHNIQUE
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BIOLOGICALLY INSPIRED
ROBOTICS GROUP (BIRG)

Modelisation and Simulation of Climbing Robots

Master Project

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2008

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Abstract

This project is a part of a bigger project aiming to develop bio-inspired climbing robots for space exploration. My goal is to provide a tool to simulate the physics of those robots, design them and test their controllers. Therefore my project is divided into three main steps.

The first step consists in developing a physical plugin for Webots in order to be able to simulate the bio-inspired adhesion mechanism that is developed in the research laboratory.

The second step aims to create 3D models of two different robots in Webots. These models will reflect as accurately as possible the true mechanics of the ones developed in the Mechanical Engineering Laboratory of Dr. Carlo Menon at Simon Fraser University. The first robot will consist in a six-legged spider-like robot with 6 DOFs on each leg. The second one will consist in a simple four-legged gecko-like robot.

The third step will study the walking mechanisms of the geckos and design a robust walking pattern using CPG's with feedback for the gecko robot previously modeled. More precisely, the study will focus on the mechanism at the level of a leg; how to optimize the attachment of the leg through adhesion and the reflexes occurring at this level.

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1 Introduction

The design of robust space rovers for the exploration of extra-terrestrial planets is a topic of great interest. These last decades, the idea of using biologically-inspired vehicles for this purpose is being more and more studied. Indeed animals have evolved for hundreds of years, their mechanical and control systems are able to deal with all sorts of situations and resist strong perturbations. It is then natural to try to mimic their capacity in order to design robust vehicles able to face the wrecked grounds of extra-terrestrial planets.

The main idea of this project is to take inspiration of the adhesion mechanism of the geckos which is bla bla bla and develop with this mechanism small robots that could climb and face any wrecked ground.

Develop:

Previous robotics project (geckos, esa spider)

Adhesion mechanism

Reflex single leg level , Muscles–spindles, GTO

CPG → oscillators

2 Adhesion physic plug-in

2.1 Introduction

The Webots simulation program does not implement any adhesion mechanism in its actual version. However it allows the user to define specific physics plugins and thus the modification of the physic properties of any object of the simulation, the addition of new forces or, more generally, the modelisation of new behaviors for all or any particular objects of the simulation. This also allows the user to define particular handmade sensors or other actuators that do not actually exist in Webots. Therefore, an adhesion model should be defined in order to create the plugin for Webots.

The accurate modelisation of the adhesion mechanism is a key part of this project. Simulations and optimizations of the different gaits of the robots rely mainly on an accurate model of this mechanism. Many recent studies have described the adhesion and friction in gecko toe attachment and detachment. (Autumn, Dittmore, Santos, Spenko, & Cutkosky, 2006) (Autumn & Peattie, 2002) (Tian, et al., 2006). Most of these studies review the mechanism occurring at a nano-scale, like the attachment or detachment of single setae and spatulae (nano-hair) and the force acting at this level. (maybe put a picture here). Most of these papers also study the maximum pulling force that geckos can handle or the maximum pulling angle before detachment. However fewer papers try to define an accurate macro-scale model that could be used for our simulation. The ESA report (cf ESA) defines a mechanical and elastic model of the adhesion system of spider. They developed a model based on the hierarchical adhesion structure that gives the ability to spiders and geckos to adapt to different surfaces. In this report they model each spatula by a spring element that can bend and store energy. Then the adhesion force is opposed to the elastic force in each spatula, yielding a discretized model of the forces along the contact surface. When pulling, the elastic force opposes to the adhesion force and leads at a certain point to the rupture of the contact between springs (spatula) and surface, thus leading to a progressive detachment of the entire surface. The idea of modeling local forces will be kept in this paper, however with a different approach than the spring model. Indeed the spring model is used particularly to reflect the adhesion on rough surface; however in our simulations only the ideal case of flat surfaces is considered.

Most of the papers reviewed focus on a close modeling on the adhesion characteristics of the animals. However in this paper we are trying to model the main characteristics and adhesion properties of the dry adhesive developed here for the purpose of the robot. (link to Dan Sameoto's defense thesis).

The developed model also has to take into account some the limitation induced by Webots and some simplification in order to keep the computational time

reasonable. The main idea of the Webots plugin implemented in this paper is to extend the collision detection only for the sticky objects; if a sticky object collides any surface, the collision is analyzed and the two objects are potentially glued together to simulate the adhesion. Then the shear and stress forces are analyzed locally to model a realistic detachment behavior.

2.2 Model of attachment and detachment

The attachment mechanism of the dry adhesive is relatively simple; a good angle of approach in order to maximize the contact surface and some pressure are the two key elements to obtain a good attachment. Furthermore, the maximum adhesion force is obtained after a few delay, required for the dry adhesive to completely adhere the surface.

The detachment mechanism, in the contrary, is much more complicated. It depends on many factors such as pulling angle, peeling mechanism, the size of the contacting surface area and particularly the stress and shear occurring on the local areas of the surface. Webots cannot retrieve such local data, but is able to retrieve the forces and moments acting on a joint; in our case the equivalent of the ankle joint; its position is represented by a red dot on Figure 1; with those data, a mathematical model can be developed to determine the forces occurring at each point of the interface between the paw and the ground surface. This allows us to model more accurately the detachment mechanism.

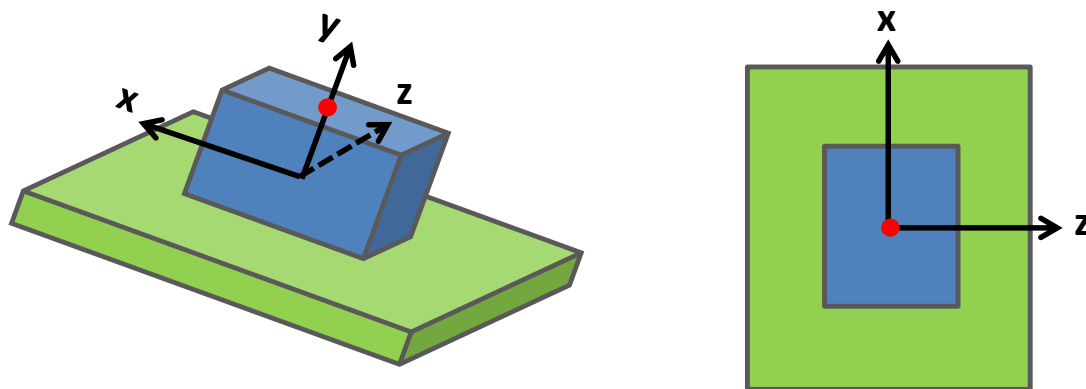


Figure 1: Lateral and top view of an object (blue) colliding a surface (green) with the frame axis of the object.

On the figure above, we can see the frame axis, relative to the object, used for the model. The pulling or pressing force and the moments acting on the object are retrieved at the top of the object (red point) and used to compute the shear and stress locally at the interface.

Note the model described here assumes a robotic application and particularly legged robots; therefore in this particular case, as it is not possible in Webots to directly retrieve the forces acting on the object, the easiest way to obtain the forces acting on a paw is to retrieve the force acting on the ankle joint linking the adhering object (paw) and the end-leg. Note that this ankle joint could be replaced by an unmovable joint whose only purpose would be to retrieve the required information for any other cases.

2.2.1 Attachment

Still To define → (real experiments are being done in the lab)

modify number of contacting points according to:

(I would say according to speed, angle of approach and [contacting surface?])

And rapidly increasing while no pulling force !

2.2.2 Detachment

2.2.2.1 Local shear and stress

In this section a model of the forces occurring at the interface between the paw and the ground is described. We make the strong assumption to consider the paws as rigid bodies on which some forces and torque occurs and the adhesion bonds are considered as cantilever beams. With respect to those assumptions, we can compute the shear and stress occurring locally on each beam along the contacting surface.

The three following equations define the local stress (σ_y) and shear (τ_x, τ_z) along the contacting surface. Those equations will be used to determine locally if the adhesion is holding by simulating the forces acting at each points of the surface.

$$\sigma_y(x, z) = \frac{F_y}{b \cdot h} + \frac{M_x \cdot z}{b \cdot h^3 / 12} + \frac{M_z \cdot x}{h \cdot b^3 / 12} \quad (2)$$

$$\tau_x(z) = \frac{F_x}{2 \cdot (h \cdot b^3 / 12)} * \left(\frac{h^2}{4} - z^2 \right) \quad (3)$$

$$\tau_z(x) = \frac{F_z}{2 \cdot (b \cdot h^3 / 12)} * \left(\frac{b^2}{4} - x^2 \right) \quad (4)$$

where $F_{x,y,z}$ are the forces acting on the object along each axis (shown on Figure 1), $M_{x,z}$ are the moments acting on the object along the x and z axis and finally b and h are the width and height of the contacting surface.

2.2.2.2 Rupture of adhesion bond

Once the force occurring at each point is determined through local shear and stress forces, the condition for the breaking of the adhesive bond at each point has to be determined. For that purpose, the shear and stress forces on a single point are combined in the Von Mises Equivalent Stress equation (5).

$$\frac{1}{\sqrt{2}} * \sqrt{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6\tau_{yz}^2 + 6\tau_{zz}^2 + 6\tau_{xy}^2} \quad (5)$$

This equation is usually used to determine the rupture point of a solid material (ref). If the Equivalent Stress condition is higher than a maximal value, dependant on the material, then the material is said to be broken at this point. In our particular case, assuming rigid bodies and cantilever beams, this equation can be used to represent the rupture of the bond. Furthermore, we only have the shear and stress occurring in one plane (eq. 2, 3 & 4); which allows the following simplification of equation 5:

$$\sigma_{vM} = \frac{1}{\sqrt{2}} * \sqrt{2\sigma_y^2 + 6\tau_x^2 + 6\tau_z^2} \quad (6)$$

When σ_{vM} is bigger than an experimental threshold value σ_{vT} (still to be determined) then the bond is considered broken and does not participate anymore in adhesion. However as we can remark in equation 6, the result of the Equivalent stress is the same when pulling or pushing an object, which is true for the breaking of an object but not correct in case of the rupture of an adhesion bond. Therefore according to the sign of the stress force σ_y , two cases are taken into account. When the stress force is toward the ground (pushing), σ_y in equation 6 is set to 0 and the threshold is corrected with the frictional force due to this stress; extended from the JKR model theory (ref: Adhesive Handbook, 264,5 → develop more)

To resume, the breaking of bonds is ruled by the two following equations:

When pulling ($\sigma_y \geq 0$):

$$\sigma_{vM} \geq \sigma_{vT} \quad (7)$$

When pushing ($\sigma_y < 0$):

$$\sigma_{vM}(\sigma_y = 0) \geq \mu * \sigma_y + \sigma_{vT} \quad (8)$$

where μ represents the (negative) coefficient of friction and σ_{vT} represents the experimental threshold.

2.3 Implementation

2.3.1 Object classes

In order to be generic and reusable for different robots, the adhesion plugin has been developed with an oriented-object implementation. Each sticky object is represented by a class; which allows defining easily many different sticky objects with potentially different characteristics.

The physic plug-in is divided into four main files; "main.cpp", "adhesive.cpp", "stickyObject.cpp" and "vector3D.cpp". The classes are shown on Figure 2 with their most relevant variables and functions.

The first class, *Main*, corresponds to the entry point for the physics plugin; it defines a new Adhesion object and calls the functions of this object to override the required Webots physics plugin functions. It is also responsible to clean the memory between two simulations.

The *Adhesive* class is the main class of the plugin; it initializes all the parameters of the plugin and creates all the adhesive objects corresponding to the ones present in the simulation world (this creation is hard-coded, using the name of the objects as defined in the Webots world to retrieve them). The adhesion class also handles the redefinition of the collision mechanism as described in section 2.3.2.1.

The *StickyObject* class defines the properties of a sticky object and contains various functions related to the adhesion and the parameters of the object. The main functions are the computation of the local sheer and stress along the surface as defined in section 2.2.2, the update of the forces acting on this object through the *computeAndUpdateFeedback()* function and the reevaluation of the adhesion force through the *testAdhesionEfficiency()* function.

Finally the *Vector3D* class, not shown in the figure below, is a small library to simplify the usage of 3D vectors; it contains most possible vector operations.

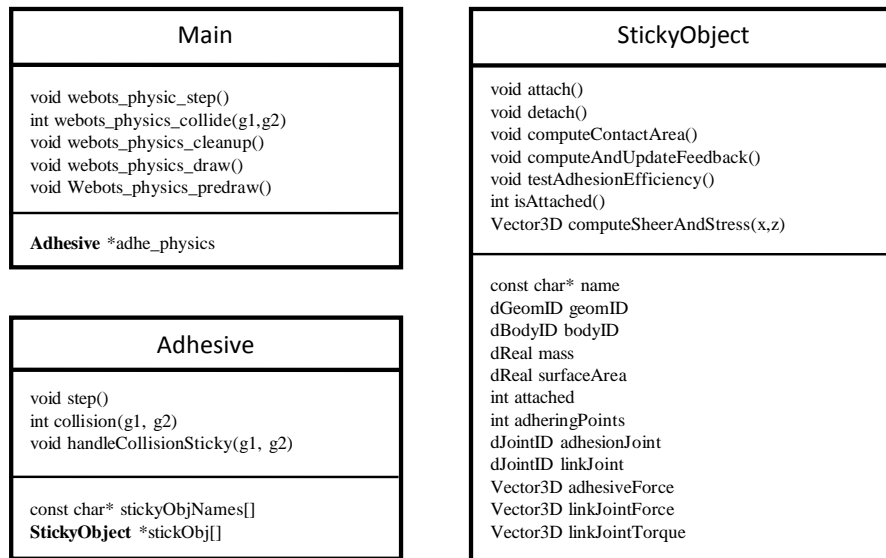


Figure 2: Object representation

2.3.2 A physics step

The execution scheme of a physics plugin by Webots is shown on Figure 3, with the four main functions of a simulation step; the update of the servos with the addition of the forces, the detection and handling of the potential collisions, the step function to advance the world state of a time Δt and finally the suppression of the joints created to handle the collisions contact.

The adhesive physics plugin implemented in this paper mainly redefines the collision detection during the *webots_physics_collide()* function and modifies the collision behavior for the adhesive objects. Then the plugin modify the behavior of these objects in the *webots_physics_step()* function to simulate the adhesion mechanism.

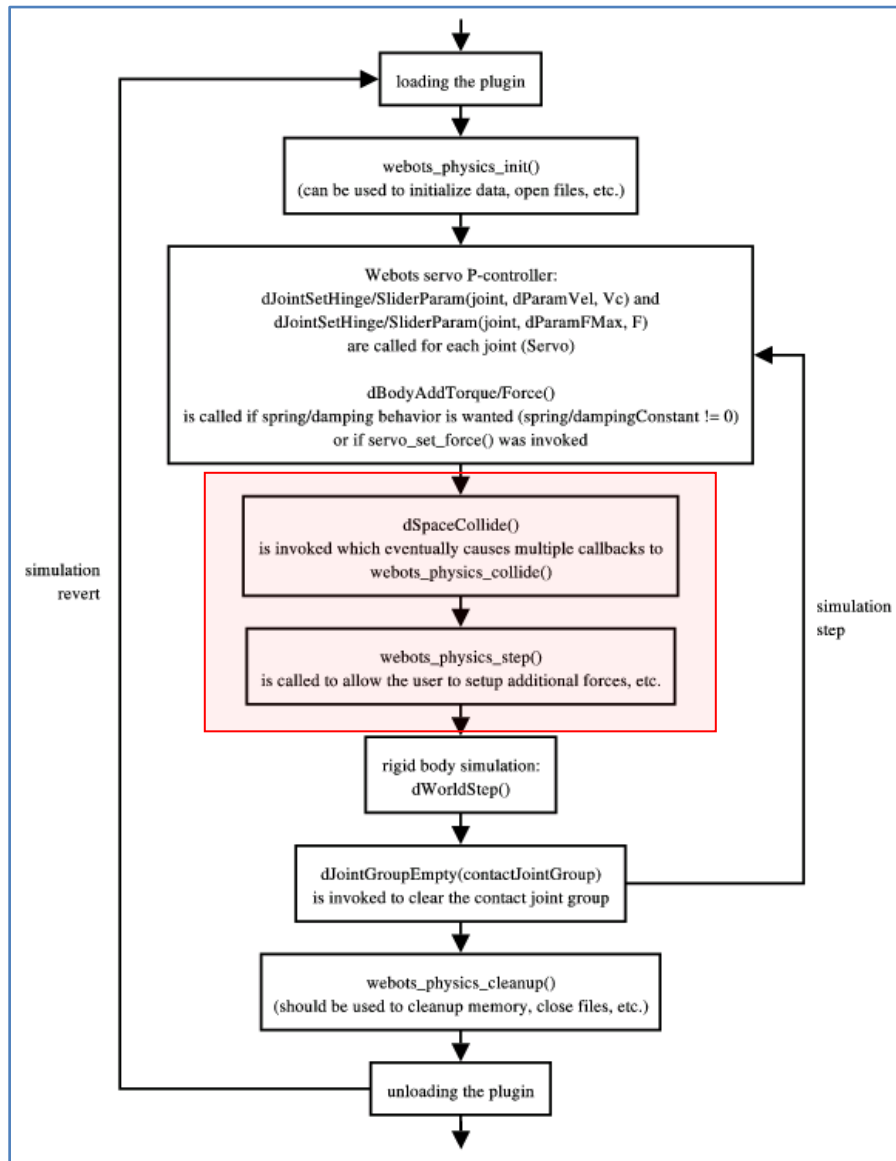


Figure 3: Physics Plugin Execution Scheme (Webots Reference Manual)

2.3.2.1 Collision detection

For each potential collision occurring in the world, a test is executed to determine if one of the objects in collision is sticky object. If it is not the case, then the collision is handled “classically” by Webots. If one of the colliding objects is a sticky object, the number of points that are colliding are determined. There may potentially be no contacting points because the collision detection starts when there might be a potential collision and not at the collision time itself. If the number of colliding points is two or less, no adhesion surface exist and thus there won't be any adhesion occurring; therefore a collision occurs but with special parameters set to mimic a small spongy effect due to the adhesion material. If the number of colliding points is bigger or equal to three, then the success of the attachment is tested according to the instantaneous speed of the object, its

angle of approach and the area of contact. Finally if the attachment was successful, the object is glued to the surface and the parameters of the object are updated to define the quality of the adhesion as explained in the following section.

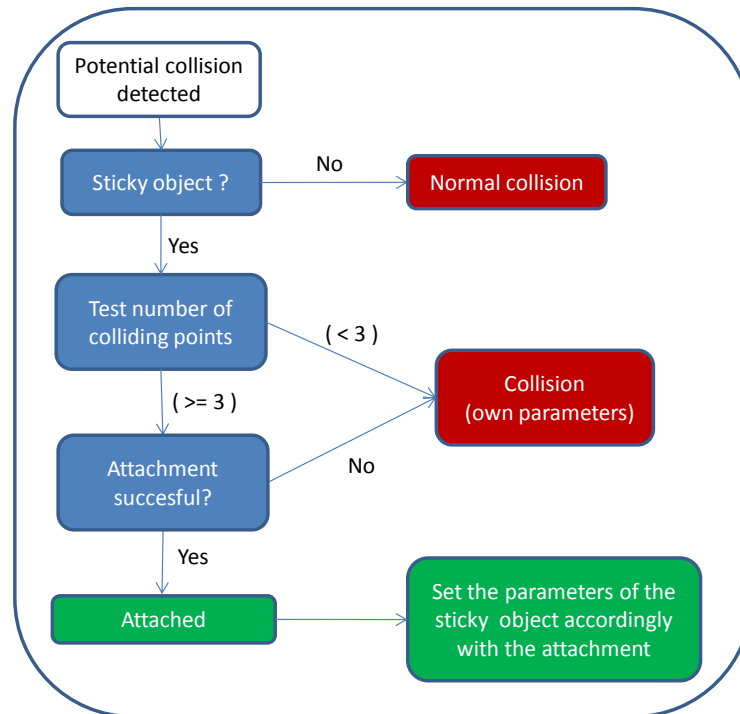


Figure 4: Execution scheme of the collision detection

2.3.2.2 Attachment

The attachment mechanism is simulated in Webots by adding a fixed joint at the position on contact between the adhering object and contacting object. The adhering object won't be able to move as long as the fixed joint remains active. The joint will be deactivated on detachment according to the algorithm of section 2.3.2.3. The adhesion quality can be modulated during the attachment phase by setting the number of surface points that are adhering and thus modulating the adhesion force.

Define exactly how this is going to be modulated (in accordance with what is going to be defined in 2.2.1)

2.3.2.3 Detachment

The model of a partial detachment of the adhesion surface is handled with the simulation of the forces acting at the different points of the simulated surface. This is achieved by discretizing the surface and allows a more accurate simulation of the detachment mechanism. The adhesion force that an attached object is subject to is recomputed at each time step (equivalent to a physic step) according to the number of local points currently adhering. With

such a mechanism, as soon as some points begin to detach, the adhesion force decreases and at the next simulation step, more points will detach due to the adhesion force being smaller. Remark that the maximum number of points used to simulate a surface can be modified according to the number of adhering objects of the simulation and the computer capabilities in order to be able to tune between an acceptable computation time and a more accurate model.

The implementation of the algorithm used in the adhesion plugin is shown on Figure 5. Note that the loop “*For(everyLocalPoint of the object)*” represents a loop over all the contacting surface in the x and z direction (cf. Figure 2) to simulate all the points of the 2D surface.

```
At each physic step, Do:
  For(every sticky object attached)
    #attachedPoints = MAX_ATTACHEDPOINTS
    For(everyLocalPoint of the object)
      computeLocalSheerAndStress(x,z)
      If(func(localSheerAndStress) > threshold)
        #attachedPoints = #attachedPoints-1
      endif
    endFor
    updateAdhesionForce(#attachedPoints)
  endFor
endDo
```

Figure 5: Detachment algorithm

A simple test to plot the minimal force required to detach a weightless object has been handled in order to be able to compare the behavior of the model with reality. A weightless sticky cube is static on a flat surface and an increasing force is pulling the cube object through a constant angle. The minimal force required to detach the object is recorded for different pulling angles. The result is shown on Figure 6. Note that an angle of 0 degree represents a vertical pulling force and an angle of 90 degrees a horizontal pulling force. We can observe that the optimal pulling angle is 45 degrees and that the required force is growing when pulling from 85-90 degrees. The force required when partially pushing the object (>90 degrees) rapidly increase after some oscillation between 100-125 degrees. These oscillation have to be better studied to understand their origin. Note that the values of the equations have been set to empirical data gathered by Dan Sameoto while working on the dry adhesive; those vealue are rough

approximations and should be fitted with value gathered during real experiments.

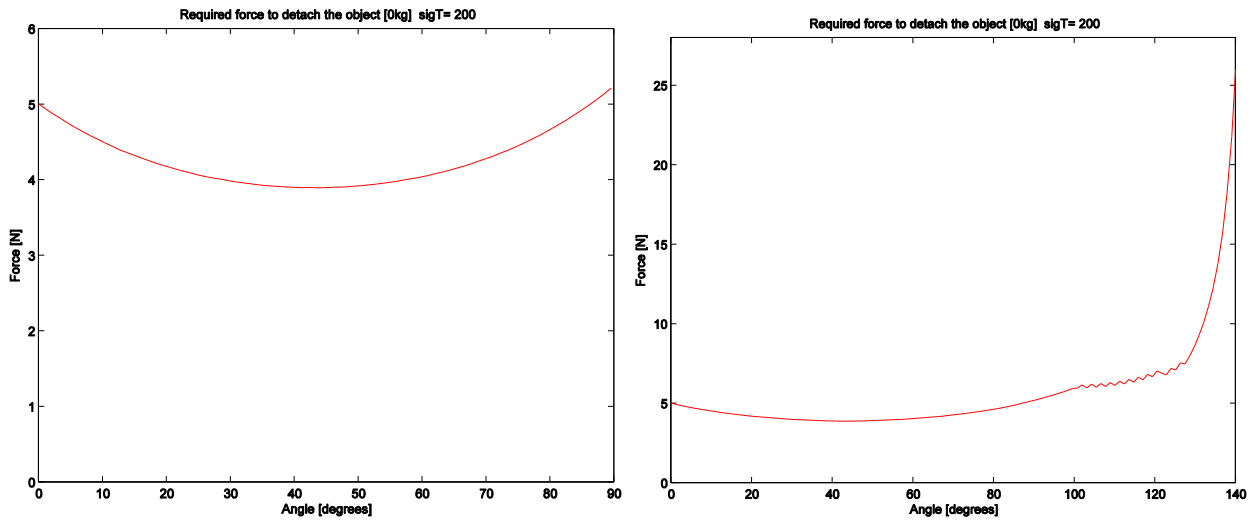


Figure 6: Minimal required force to detach a weightless object.

Actually, no test in reality has been handled, but it will be done during the upcoming weeks; and both results will be compared to validate the mathematical model.

3 Robots modelisation (DRAFT)

3.1 Introduction

Two different robots will be modelised for the Webots simulation. The first one, a spider robot, will accurately reflect the robot actually developed by Yasong Li in Carlo Menon's laboratory at SFU.

Then a simple gecko-like robot has been modeled in order to study closer the adhesion of a paw and how to improve this crucial step. (Further chapter, coming soon). This robot will not reflect any real robot, but will be inspired by biology and extremely simple to allow a close study of the leg and foot mechanism without having to worry too much about the behavior of a complex body.

3.2 Spider robot

3.2.1 Real spider robot

The spider robot is a 6-legged robot. It has been specially designed with a light weight structure in order to be able to climb walls. Each of its legs has 3-DOF and a compliant joint at the level of the ankle in order to maximize the contact surface of the paws to the ground. Each paw has a sticky material that allows the spider to adhere to surfaces. As we can see on Figure 7, the spider is still under development and all its structure is not fully defined. The feet are particularly of higher importance for the robustness of the robot. Indeed the feet are one of the key part of the attachment mechanism and should as much as possible facilitate the adhesion of the paws. Therefore different structures are still investigated. Furthermore the motors currently used should be replaced in long-term by hydraulic motors. Also the initial idea is to have all the motors on the central platform of the spider instead of the actual version where some of the motors are at the position of the knees.

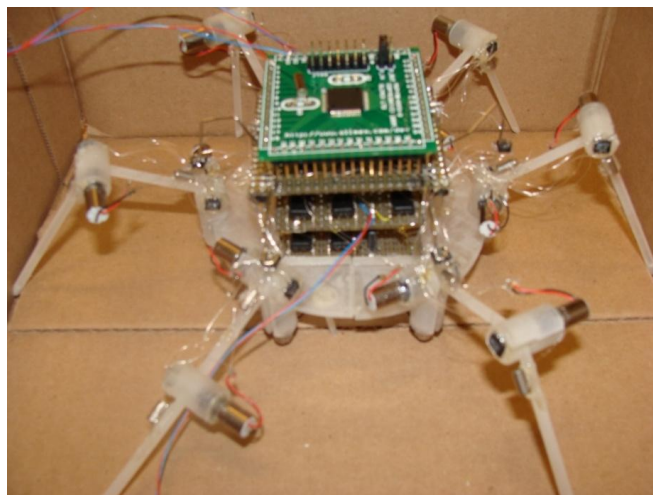


Figure 7: Photo of the spider robot (temporary picture)

3.2.2 Schema of the spider

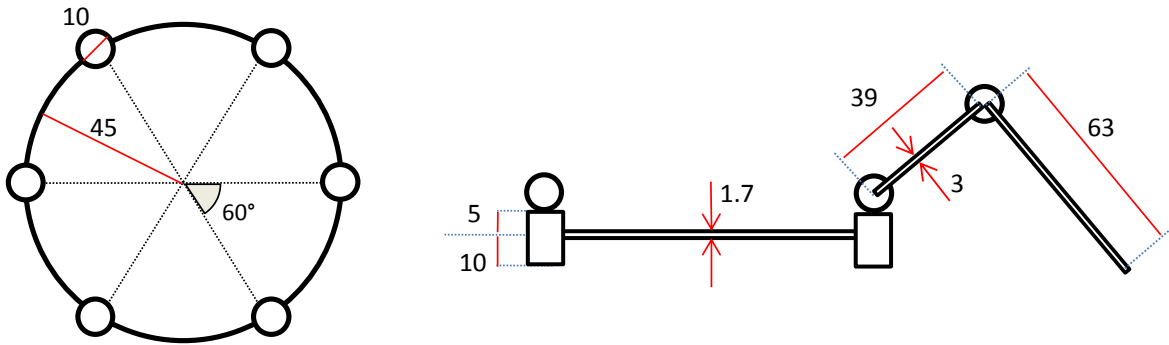


Figure 8: Top-view and lateral-view schemas of the spider.
All values are in millimeters.

This schema resumes the dimension and angles of the different elements of the robot. All the dimensions described here have been respected in the model designed in Webots. Every circle in the schema represents one motor on the robot allowing one degree-of-freedom to the robot. The compliant ankle is not shown here as its final shape is actually not defined with certainty and will be simplified in Webots by spheres.

3.2.3 Webots model

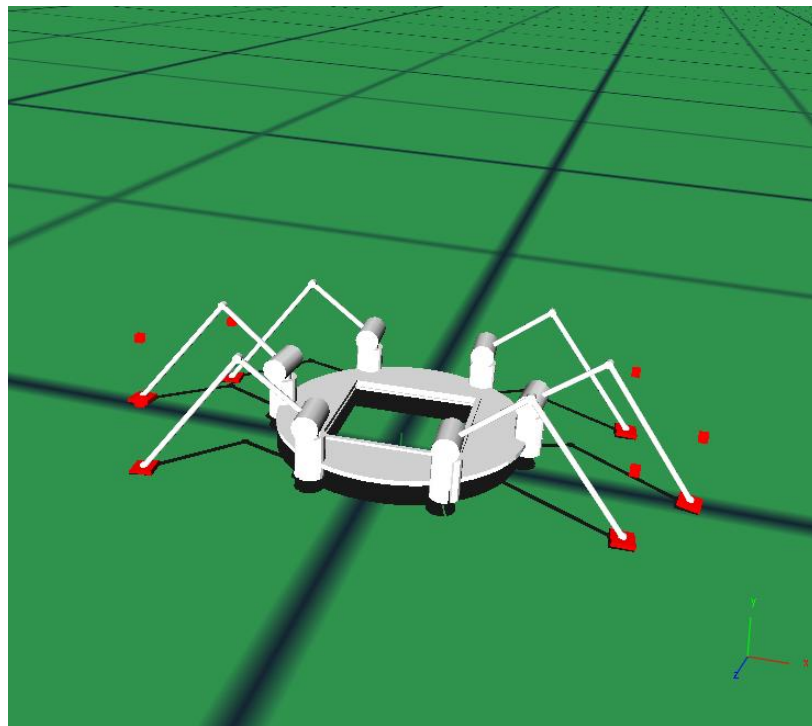


Figure 9: Screenshot of the modeled spider robot (temporary)

The model realized in Webots is a mixture of the current design and the final designed design. Therefore, the shape of the knees servos has been omitted and the weight of the legs can be assumed to be negligible; however the paws will still have some weight. Furthermore the paws have been modeled as simple spheres for two reasons; the first one is to simplify the simulation as simulating a 3 DOF ankle with a elastic paw during the simulation would be quite unhandy and it would be difficult to obtain a good behavior with this scheme. The second reason is that the design of the paws is not fully defined and that the attachment and detachment mechanisms of these paws are actually being included directly into the mathematical model of adhesion to be able to reflect more accurately the real mechanism independently of the simulation.

Note that figure 9 is an old design where the feet are modeled as cube and not as spheres. It also has the 3 DOF ankles yielding some ground adaptation problems during the simulation.

3.3 Gecko robot

Still to be modeled

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