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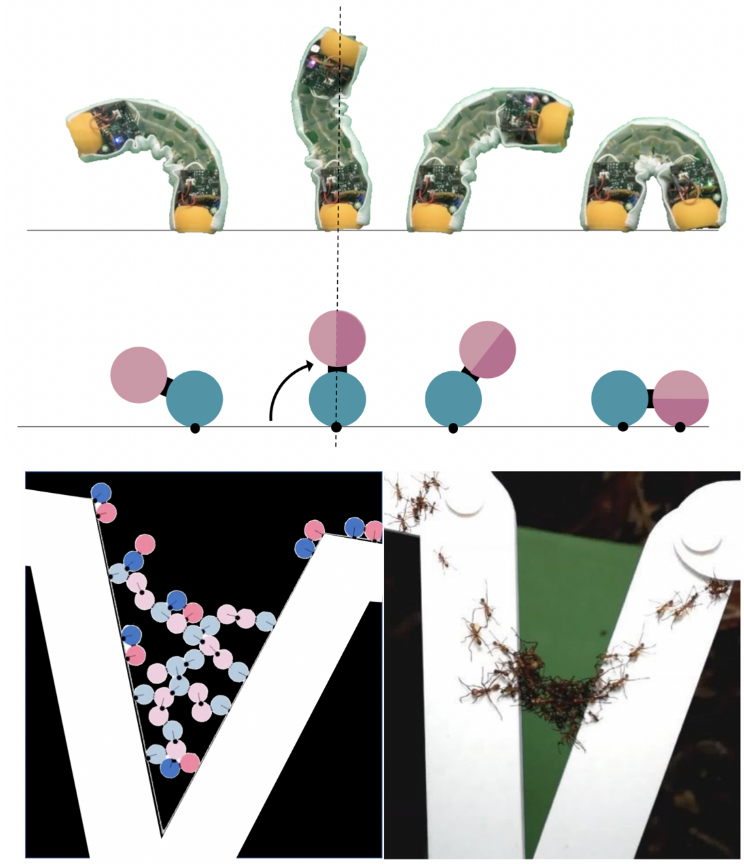
Self-assembly of soft-robots in simulation inspired by army ant bridge behavior

Lucie Houel



Professor: Radhika Nagpal, Alcherio Martinoli
Assistant: Melinda Malley, Faezeh Rahbar

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Title of the project

Self-Assembly of Soft-Robots in Simulation Inspired by Army Ant Bridge Behavior

Author

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Project description

While there are many potential applications for insect-inspired self-assembly in robotics, the process of self-assembly is not well understood. Unlike human construction, there is no central command and no blueprint of the desired structure; bridges instead evolve according to sensory inputs and local rules. The army ant bridges are a great example of this -- bridges often form as shortcuts across rough terrain, and they form only when there is congestion. It is believed that the bridges form because ants start climbing over each other, and ants that get walked over decide to stay put as part of the bridge. In most cases this is self-stabilizing: the bridge allows traffic to flow better and removes congestion, which then automatically stops the bridge from growing further. If the traffic goes down or stops altogether, then the ants in the bridge that can leave start leaving, and eventually the bridge disappears altogether. The goal of the project conducted within the Self-Organizing Systems Research Group of Harvard SEAS is to uncover the methods army ants use to form functional bridges and apply what is learned to forming functional structures in self-assembling robot swarms. This involves the co-design of the necessary robot hardware and the development of self-assembly algorithms through the study of natural systems and modeling natural and robotic systems in simulation. While a new soft climbing robot that can self-assemble into structures like bridges/towers/chains, inspired by how army ants self-assemble is currently being designing This master project would involve helping to create/discover the algorithms that lead to such adaptive structures.

A first step will be creating a good physics-based simulator, where one can explore robot controllers easily. The next step will be to study algorithm versions that reliably create self-stabilizing bridges that dissolve when traffic is stopped, similar to the experiments that were done with ants. And finally, the goal would to be able to come up with a model that helps understand how geometry and traffic predicts when and where bridges will be formed, and extend this to other structures/terrains (e.g ramps or towers).

Tasks

- Read the Box2D documentation and choose a coding environment.
- Familiarize with Box2D, determine its strengths and limitations, eventually compare with other existing 2D simulators.
- Create a good physics-based 2D simulator using box2D. Verification will be done by implementing one robot and then several robots moving in a horizontal box with gravity. Collision between 2 robots and more should also be tested to verify the good implementation.
- Verify the auto-formation of the bridges in presence of a V-terrain and/or a ramp. The first step will be to set infinite delay

for the ants in the bridge. Verify that the bridge still form with a finite delay.

- Explicit the parameters influencing the formation (ant flow, V-width…) by conducting several experiments in the simulation:
  - does a bridge form stably
  - how long does it take
  - how many robots are in the bridge
  - what is the new path length
  - Can we explain fully the relationship between (terrain geometry, traffic-value, and bridge formed)?
- Prove that the bridge is auto-stabilizing
- Prove that the self-dissolution is possible and characterize the dissolution: what parameters are of influence.
- Try to express a model that would summarize the influence of each parameter over the formation of self-stabilizing bridges.
- If the hardware allows so, try to verify the dissolution hypothesis on the robot.

General consideration:

- A weekly meeting is set with the supervisor on-site
- Consider writing documentation and readme files as you proceed through testing and evaluations.
- The final software code should be clean, commented, and accompanied by documentation files.

Oral presentations

The date and time of the intermediate and final presentations will be specified mutually by the student, supervisor, and professor. Presentations and accompanying slides must be in English and in MS Powerpoint format. Rehearsal presentations with the project supervisor before the official talk are strongly encouraged.

Final report

All of the student's work shall be submitted on a CD (report, presentation, source code, documentation, media, etc.). No paper copy of the report will be required by DISAL although some paper copies may be requested by the project supervisor for his/her records and/or the corresponding teaching program (section). The final report must use the standard cover page and include a copy of this extended proposal just after the cover page. The report must be submitted in PDF format, and the source files (MS Word recommended, Latex accepted) should be contained in the CD-ROM, as well as the final presentation. A complete draft of the report must be submitted to the responsible supervisor at least *two weeks* before the final deadline. Revisions and comments will be returned in a timely fashion and will need to be incorporated into the final version of the report.

Web visibility

The student's name will be listed on the DISAL web site (under http://disal.epfl.ch/people/) and hyperlinked to an appropriate home page if possible (either personal, or a brief page on people.epfl.ch). At the end of the project, with the help of the supervisor, a 1-page summary, a definitive project abstract, and one picture of the project will be posted (see http://disal.epfl.ch/teaching/student_projects/ for examples). It should be finalized and approved by the supervisor. Additional movies and pictures can be posted according to DISAL guidelines and after supervisor approval. This page will remain on the DISAL site under the section "past student projects" and the student's name will be moved to the "alumni" section. The project will not be considered concluded until the dedicated web page is available on-line.

Supervision	Faezeh Rahbar
Place of work	Harvard
Recommended literature	Add references and manuals here

Contents

Chapter 1 Introduction

Background and motivation

Nature is a constant source of inspiration for scientists. Roboticists are more and more intrigued by social and collaborative insects. Working in team, small individuals of a colony are able to accomplish tasks that require collaboration, such as building structures that are several orders of magnitude larger than themselves. Some of these structures are self-assembled; the building material is the insects themselves. At least 18 different types of structures exist [1] such as bivouacs, rafts or chains (Figure 1.1). The purpose of this kind of structure can vary from controlling the temperature to surviving an emergency situation such as flood, or even improving efficiency for migration or for prey conveyance. Even more impressive, the self-assembled structures are often highly adaptable. Nests can repair themselves after being damaged by a falling branch, and bridges change depending on the traffic patterns. Overall, they protect the system from the natural fluctuations of temperature [1], flow or terrain. Social insects are able to do this without centralized supervision. Scientists currently believe that simple local rules are sufficient to obtain such complex collaborative behaviors.

(a) Army ant bivouac (b) Fire ant raft[2] (c) Army ant bridge[3]

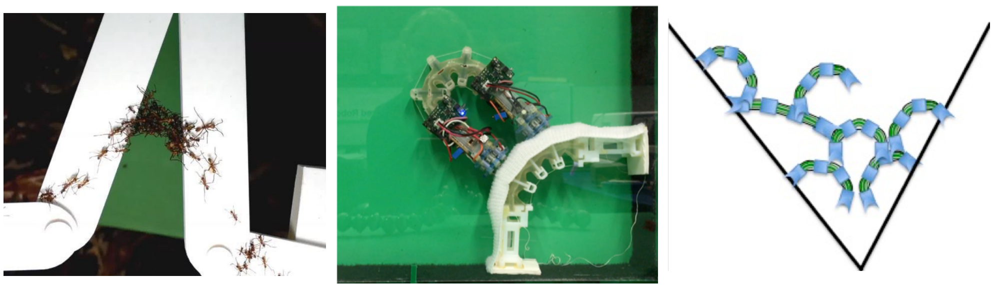
Figure 1.1: Examples of self-assembled insect structures found in nature.

The application of self-assembly principle to robotics could be highly beneficial to the field. Smaller, cheaper, and simpler robots could collaborate in order to overcome difficult tasks they would not be able to accomplish by themselves, or navigate on rough and damaged terrains. It could be especially efficient when robots are exploring unknown and rapidly changing terrains. Robots would then be able to assemble and disassemble into different kind of structures to adapt to the obstacles they encounter. In addition, relying on the behavior of several combined robots might be less impacted by the potential failure of one of them, as the collaboration would compensate for it. Even if self-assembly is a growing trend in robotics, the field still faces many challenges. The limited variety of shapes that can be formed is one of them, miniaturization of the hardware is another one. Often the individual robot is inert by itself and no real locomotion is possible if not assembled to others. This is particularly true with reconfigurable robots where the independent modules often integrate limited sensing of their environment [4].

Objective

The team at the Self-Organizing Systems Research Group at Harvard (SSR) is working on designing a self-assembling robot swarm that would be able to reproduce the behavior of army ants, focusing on bridge formation (Figure 1.2). The first step required to accomplish this goal is to design robots that are able to climb over each other. A first version of such robots has been created [5]. A second aspect of the project is to develop algorithms or local rules that would lead a swarm of robots assemble into mechanically stable amorphous structures. The final objective is to be able to test the algorithm on a small swarm.

Because the mechanisms involved in the real army ant bridge formation are still not perfectly understood, it is necessary to test different possibilities and variations of rules in simulation. This report will address this last aspect of the project. It will describe the implementation of the simulator and verify that simple rules can indeed lead to a self-formation and dissolution of a stable structure. This part of the project will also study how some parameters can influence the bridge formation and how we might take advantage of the observations to control the bridge formation.



(a) Army ants creating a bridge over a V-shaped gap [6].

(b) Moving Flippy robot climbing over a static robot [7].

(c) Concept drawing of robots forming a 2D bridge over a V-shaped hole[7].

Figure 1.2

Chapter 2 State of the art

2.1 Army Ant bridge formation

2.1.1 Generality

Several types of structure exist in insect societies such as bivouac, curtains, and bridges. These kind of complex formations are found in various species: from the ant to the bees. These kind of structure, where individuals grip onto each other, have been defined as "self-assemblages" [1]. They are generally at the midway between the individual and the whole colony as they often involve teams smaller than the entire colony.

In this project, the focus will be put on the bridges structure in the army ant society. In this insect population, bridge formation is critical as it can lead to a gain in efficiency in the prey conveyance task. The army ants are not only a group of predator, they are also nomadic and have to run over long and sometimes damaged paths. In fact, the quality of the terrain is essential to the formation of bridges. Some terrains that are relatively smooth may not lead to any bridge formation whereas, on really rough ones, a high density of bridges might be observed. The distance bridged by those structures over a gap can be significant (several order of magnitude bigger than the ant individual size [1]). It has also been observed that it is not always bridges over gap that are formed but also ramps that smooth a difficult terrain with step-up for example.

Some scientists [1] suggest that, if the number of individuals (the Eciton army ants live in colonies of over 700,000 individuals [8]) is an important parameter in the self-assembly process and that a high density is often required to form complex structure, the morphology of the ant may also be critical. Their long legs might be indispensable to be able to grip onto each other. C.Anderson and Al. [1] also highlight that some army ants stiffen and become motionless when stretched. Nonetheless, despite this potential clue regarding the self assembly of the bridge, the rules that dictate the formation and dissolution are not yet known. The most widely spread hypothesis is that it has to do with the traffic patterns and might be due to the ant immobilization when stepped over. This idea comes from the fact that the ants on the bottom of the structure, being stepped over, are under the load of the other ants, which is not the case of the ones on top of the formation. These last ones are therefor free to leave the structure anytime.

In addition, if biologists make the distinction between self-assembly and self-organization [9], this distinction is usually dropped in the robotics field. It remains interesting to observe that self-assembly may or may not require self-organization principles such as positive feedback. In the case of army ant formations, it is likely that positive feedback is somehow often involved. Indeed, it can be stated that the bridge structure has to be appealing in a certain way to other individuals so that the growth of the structure from the initial contact formation is amplified and facilitated. Evidence of such positive feedback have been found in Oecophylla longinoda chain formation where the current chain size leads to an increase in the probability that a new ant becomes part of the structure. [10]

2.1.2 Ant traffic

Ants colonies being huge (usually over 700,000 individuals [8]), it is difficult to describe the traffic precisely and uniquely. Nevertheless, we can highlight some interesting observations. One is that the ant flow is usually more organized than how it appears at first sight. Army ants are not only good at following trails, they are also able, for a certain range of density of the traffic, to collectively choose a direction for the raid [11]. It has even been observed that after a period of disorder, the ants often begin to move in the same direction. In addition, it is frequent that army ants organize as an unidirectional flow of individuals at the beginning of a raid, and progressively adapt to form two bi-directional columns when some of the ants are returning.

Regarding the flow of ant, a relatively recent study [8] showed that the army ant traffic on a V-shaped path exhibits consistent periodic dynamics.Thus they decided to use an oscillatory model to represent the traffic.

2.1.3 Bridge formation and evolution

As mentioned previously, it is not well understood how the bridges form and how they self-stabilize or if they even do so. Thus real experiments with living ants have been conducted [8] and [6] to discover what parameters may influence the bridge formation and to what extend.

At the scale of the individual, it is not rare to observe a single ant plugging into a pothole in the Eciton Burchellii specie (see Figure 2.1). It has been shown [12] that this plugging behavior significantly enhances the prey foraging task in the sense that it helps the ant flow reach a maximum speed. In addition, the ant size usually corresponds the one of the hole. While it might be for prey conveyance optimization (as bigger ant are able to transport bigger prey), another hypothesis is that an inadequate size of the ant plugging "may create a substandard substrate for others to run over", thus leading to a slow down of the crossing ants.

Figure 2.1: Researchers inserted planks drilled with different-sized holes on army ants' trails. An ant that fit the hole would plug it for the other ants. This allowed prey-laden foragers to run back to the nest faster. [12]

When larger gaps are bridged, the mechanism is more complex as it requires a coordination between several individuals. The results are highly variable and influenced by two major parameters: the ant traffic and the geometry of the terrain

Traffic influence

Recent studies [8] show that there is a correlation between the traffic density and the bridge formation. In fact, when the traffic is stopped, a bridge that has been formed under a given ant flow quickly dissolve by itself. To formalize how the individual behavior impact the overall bridge self-assembly, Garnier and al. created a "data-driven, pseudo-spatial individual-based model of the ants' behavior" [8] They rapidly observed that the probability of finding a bridge seems to increase non linearly with the traffic intensity. When they modelled the random flow of ant with a poisson distribution, they observed that the function characterizing the evolution of the bridge stability (from stable to unstable) with the traffic value is close to being a step function. When they adapted to model an oscillatory traffic, they found that a certain precise period of the oscillation (which in their case was coherent with the "dominant oscillation period found in nature") is more likely to lead to bridge formation, whatever the amplitude of the oscillation is.

When Garnier and al. looked closer at the individuals composing the bridge, they realized that the time an individuals remains in the bridge is influenced and can be predicted by the local traffic intensity. In addition, most of the time, the bridges are composed by a stable core of ants that remain in it for the major part of the bridge's lifetime.

However, their major conclusion was that the "bridges are simultaneously highly sensitive and responsive in the face of sudden alteration of traffic on the trail. Thus this living architecture filters appropriately variations in traffic, discriminating between normal operating conditions and sudden, large perturbations of the foraging activity." [8]

Geometry influence

When using an horizontal apparatus which creates a V-shaped gap to do experiments with real ants, the geometry of the terrain can be controlled controlled. It is then easier to study the terrain shape influence on the bridge formation [6, 13]. The resulting observation is that the angle of the V-shape has indeed a major impact on the bridge position. The ants start to construct a bridge from the apex of the apparatus (i.e the bottom of the V-shape) and progressively migrates to the top of the gap. The distance moved by the bridge increases when the angle of the V decrease in a non-linear way[6]. In addition of affecting the migration of the bridge, the environment geometry also affect the overall shape of the structure. Jason M. Graham and al. discovered that a symmetrical V-shaped gap (respectively to the normal to the trail, Figure 2.2) usually leads to a symmetrical flat bridge. When the symmetry is broken, by differentiating the V-angles to the left and the right of the trail's normal (ϕ and θ on Figure 2.2), the bridge adapt to the geometry. Usually, the migration is higher on the side with the smaller angle.

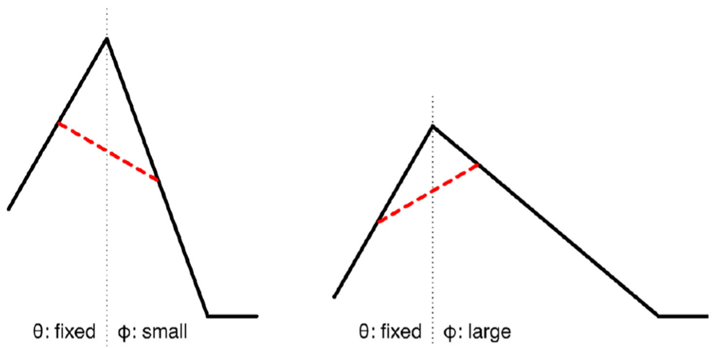


Figure 2.2: Results[13] for the predicted arrangement of optimal living bridge configurations for an asymmetric horizontal apparatus as a function of the angle ϕ with the angle θ fixed at 20°. The black line represent the apparatus path from a top view, the red line the bridge position over the gap.

2.1.4 The cost-benefit trade-off hypothesis

Even if this report will not address the cost-benefit hypothesis directly, it seemed relevant to discuss it. In fact, it could be a good perspective for future work with the simulator.

This cost-benefit trade-off hypothesis was briefly evoked in Powell and Franks' article [12] who suggested that the reason why the ant size matches the one of the pothole could be that it maximizes the prey conveyance efficiency. More recently, this trade-off idea is defended, among others, by Chris R. Reid and al. in [6] and later on by Jason M. Graham and al. in [13].

This approach is motivated by the simple observation that the army ants are doing prey foraging only for a limited amount of time per day [1]. Thus they might have to maximize their efficiency in doing so to counterbalance the restricted time window. A good way to improve the prey delivery rate is to ensure that the traffic flow is optimum. In damaged terrains, it can require the formation of pothole plugs or bridges. Nonetheless, every ant involved in such formation is an ant that cannot participate in the prey delivery task anymore. Thus, in the model described in the two aforementioned articles, the benefit is the travel distance saved and the cost is the immobilization of ants that are then not available to participate in other tasks.

The experiments conducted with real ants tend to validate this hypothesis. They observed that the bridge starts to construct from the bottom corner of the V shape apparatus they are using to do the experiments. Then it quickly migrates toward the top. However it never actually reaches the top of the gap which corresponds to the actual shortest path, staying in a kind of in middle position. They believe that the position reached by the bridge corresponds to a trade-off between the cost and benefit at the colony level. Their suggestion is that this adaptation of the bridge position depending on the environment is made possible by the individuals ”modifying their likelihood to join or leave a structure based on interaction rates” [6].

2.2 Self-assembly in robotics

Many of the first studies in self-assembly robotics focused on reconfigurable robots [4, 14, 15]. Reconfigurable robotics usually involve individual robots that are not able to move by themselves, have a very limited perception of their environment and are usually controlled by a centralized supervisor. These robots generally rearrange themselves either by sliding or pivoting around each other. Thus they often rely on their environment either to assemble or disassemble and they control respectively the detaching or attaching action thanks to simple communication. It follows that the assembly process is often essentially based on stochastic rules [16].

Relatively autonomous individual robots that are able to move by themselves such as the kilobots [17] are more interesting with respect to the project. These robots have been created to test self-assembly algorithms on a large scale (1024 individuals) and are able to collaborate to form user-specified shapes [17]. Once they have determined, by local interactions, and reached their final position, they stay free of physical attachment with other robots in the fleet. Other robots swarm are able to assemble into specified 2D structure in the water but using a central control [18].

A closer example to what the overall Flippy[5] project aims to accomplish is the Swarm Bot presented by Mondada and al. [19]. They developed s-bot robots that are autonomous individually but also able to collaborate to go through more complex terrain. Indeed, each individual possesses a gripper that can be used to rigidly grasp another s-bot from the swarm allowing them to go over stairs or gap. Nonetheless, their robots are largely different from the Flippy robots as they are perfectly rigid. In addition they build structures in a linear manner (1 dimension), closer to chains than actual bridges as they are not intended to be stepped over by other robots from the swarm. These structure generally do not allow the robots to go over gaps significantly larger than the size of the robot. In the global project our simulator is part of, more complex structures will be involved. They will extend in 2-dimensions and will be used as bridges to be walked on by other robots.

This discussion laid out that a lot of the robots presented do not actually create physical links between them. In addition, most self-assembly is predetermined, it means that the fleet is programmed to reach a given shape rather than changing structure based on cues from the environment.

Chapter 3 Implementation

3.1 Objective

The objective of the simulation is to determine whether we can use some simple rules to obtain a self-stabilized bridge. Because we also want an adaptive structure that will not keep robots stuck in a useless structure, this bridge will have to dissolve when the traffic stops. The simulation will also be used to test the impact of some parameters of bridge formation such as the traffic and the geometry of the terrain. Those parameters are described in details in chapter 4.

For our simulation, we created a model of the robot where each robot can be in one of the two following states: Bridge state or Walking state. The rules determine when a robot enter or leave a given state (see Figure 3.1).

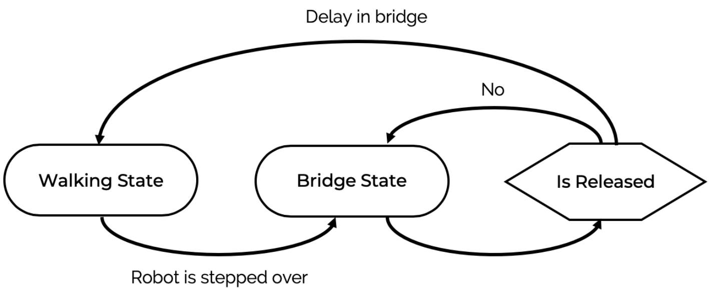


Figure 3.1: State diagram of a single robot.

As the state names describe it, when in the walking state, the robots keeps moving; while in the bridge state, the robot simply stops. The conditions for changing state can basically be described as following:

- *Entering bridge state condition:* when a robot is stepped over, it enters the bridge state.
- *Leaving bridge state condition:* When the robot perceives that it is not gripped by another robot anymore, it waits a certain delay. When this delay ends without the robot being stepped over, the robot leaves the bridge state.

While very simple, these rules can be customized. For example, the delay in the bridge state can be adapted and so does the way/frequency a robot determines that it is stepped over. Regarding how a robot is considered stepped over, this may also be defined in different ways. Choices will be detailed later on.

3.2 Simulator overview

To accomplish this goal, we implemented a simulator, where robots can be created at a specified position, at any moment in time and the terrains can be customized. The robots are able to reproduce non-trivial behaviors such as climbing on walls (Figure 3.2); For now, the robots are all walking in the same direction (clockwise). Graphically, the states are rendered in the simulation by adapting the color of the robots. The bridge state is defined by a paler set of color than the walking state (Figure 3.3).

Figure 3.2: Snapshots of the simulation of one robot in a vertical box terrain.

To study the bridge formation and dissolution, the experiments will essentially be conducted on a vertical terrain with a V-shaped gap (Figure 3.3). The robots will be created on the left of the terrain one after the other; the time span between two successive robots depends on the traffic value. As soon as they are created, they start moving in the direction of the gap.

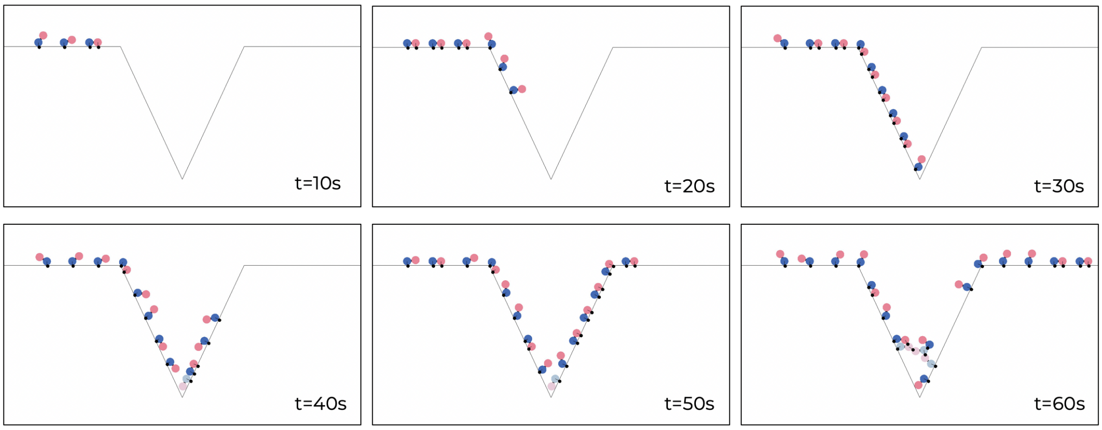


Figure 3.3: Snapshots of the simulation of several robots in a terrain with a V-shaped gap.

3.3 Design choices

3.3.1 General robot model

While the model of the robot created for the simulation is inspired by the Flippy robot [5], it aims to be a simplified and more general version. The objective was only to translate the major specificity which is that Flippy is a biped robot which moves following the flipping process described in Figure 3.4. Thus, the model has two rounded feet and moves by flipping from one foot over the other by successively creating and detaching a gripper at the extremity of the foot (see Figure 3.4). This model is perfectly rigid, and nothing from the soft body property has been translated into it.

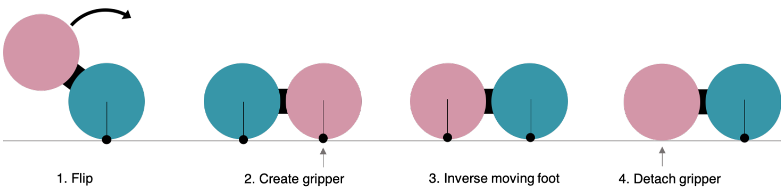


Figure 3.4: Model and locomotion of the robot

In the robot model, the feet are two rigid circles attached by a single rectangle. The flipping movement is obtained by adding a revolute motor on the joints located at the center of each foot. The gripper is a simple pin joint created at the contact point between the circular foot and the obstacle (either the ground or another robot). The model and the Flippy robot are presented in Figure 3.5.

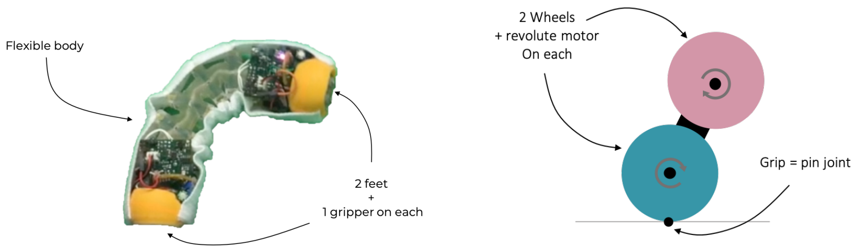


Figure 3.5: The real Flippy robot on the left and the general simplified model of the robot used in the simulation on the right.

While the model can be used solely with those basic properties, it can also be adapted to suit a given robot more specifically. In our case, we added additional conditions to get closer to the Flippy robot. Those conditions are described below.

3.3.2 Model adaptation to the Flippy robot

First condition: Single gripper per foot
In the basic model, the robot can create a gripper anywhere on the foot and the number of grippers per foot is not limited. In the Flippy robot, each foot has a single gripper, so we added this constraint to the model. Once a gripper has been created, another one belonging to the same robot cannot be created on the same foot until the first one has been detached and deleted.

Second condition: Limit angle and pushing delay
Because it is nearly impossible for the real robot to grip anything before it goes through its neutral position (where it is in plain extension, see Figure 3.6), a limit angle before the robot is able to grip has been added to the model, i.e the model will not be able to create a new joint before it rotates past a given angle from the previous joint creation. This angle has been fixed to $\pi/2$ or 90°.

However, it appears that the physical robot can sometimes still attach to terrain when the angle is $< 90°$. Indeed, even if it contacts the ground before it had gone through its neutral position, and cannot create a connection, it keeps pushing until a gripping contact is made possible. Thus we added a pushing delay after which the robot is able to create a gripper, even if it didn't rotate the required 90°. This is summarized on Figure 3.7.

Third condition: Minimum angle
In order to prevent the robot from re-gripping the exact same place two consecutive times, the robot has to move through a minimum angle before being able to grip even after the pushing delay. In all the experiments, this angle has been fixed and is $\pi/8$ i.e. 22.5°. A similar condition has already been implemented on the real robot. This condition is also useful during the dissolution phase, as it appears to reduce the number of totally blocked situations during the experiments. In fact, it gave the chance to other robots, which were in contact with the one not allowed to create a gripper, to escape the bridge.

Fourth condition: Gripping Area
Another specificity of the robot due to its single gripper per foot is that this gripper is

uni-directional. Indeed it can only grip in the direction of the movement once the neutral position has been passed (see Figure 3.6). In the model, instead of reducing the gripper position to a single point, it was restrained to a given area. This area corresponds to the half of the rounded foot that is on the side of the movement direction. This area is visible in Figure 3.6. This additional constraint was useful to reduce the number of up-grabs, although as it will appear later on, it does not get rid of all the up-grab situations. Up-grabs are to be avoided as they often block the dissolution.

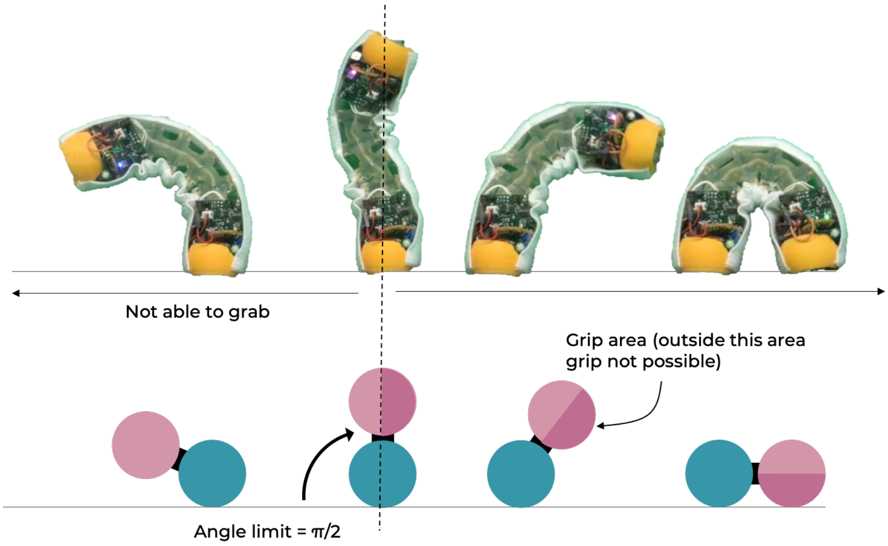


Figure 3.6: Limit angle and pushing delay conditions of the model compared to the real robot behavior

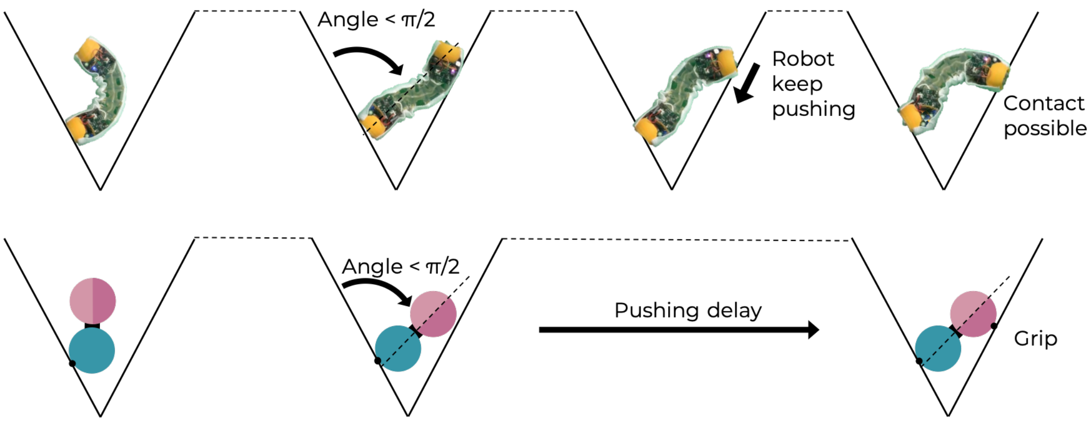


Figure 3.7: Limit angle and pushing delay conditions of the model compared to the real robot behavior

3.3.3 Differences with the Flippy robot

The major differences between the robot model and the Flippy robot are due to the simplification of the model, where the softness has been totally removed. This directly impacts the trajectory of the simulated robot. While the real robot extends its body during its movement, leading to a kind of elliptical trajectory of the gripper, the simulated robot is totally rigid, so its gripper trajectory is circular. The center of the circle is located at the center of the other foot, as can be seen in Figure 3.8. In addition, the real robot and the model do not have the same space occupancy as the real robot goes from an extended shape to a C-shape one. They will then not have the same area of possible contact.

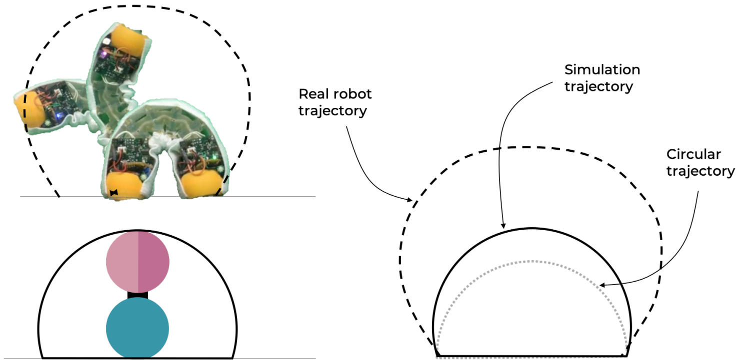


Figure 3.8: Qualitative comparison between the trajectories of the simulated robot and the real Flippy robot.

These differences lead to a major distinction in the gripping behavior of the robot. In fact, nothing prevents the simulated robots to double-grab (when two robots mutually grab each other), whereas the double grab is not possible with the real robot due to its geometry, softness, and uniqueness of its gripper position. If one wants to avoid the double-grab in the simulation, additional rules must be added. Our choice was to leave the double-grab possibility as it is, but finding rules to avoid it could be part of a future improvement.

In addition, because the simulated robot is not deformable at all, and its trajectory is a circle whose center is shifted to the center of the wheel (instead of being at the gripper position), the geometric constraints are bigger. The simulated robot can be stuck more often than the real one, leading to partial dissolution as the experiments will show. This could have been avoided by putting the rotation center closer to the gripper position respective, but then the robot might not be able to go through terrain with angle above 180°. In fact, we can express the condition on the distance d between the feet so that the robot is able to go through a ramp, which has a 90° angle, independently of its initial position. The critical case is when the attach between the feet is a single line (no thickness) and it touches the ground at the middle of its length (Figure 3.10). The following expressions can be derived (the parameters are detailed on Figure 3.10):

$$\begin{cases} l_1 & = & l_2 = l = d/2 + r \\ sin(\alpha) & = & r/l \\ \alpha & = & 45° \end{cases} \tag{3.1}$$

$$\Rightarrow d = 2(\sqrt{2} - 1).r \simeq 0.83\ r \tag{3.2}$$

where:

$l_1,\ l_2$	=	Respective length of the attach at the right and left of the ground corner
d	=	Distance between the feet
r	=	Radius of the feet
α	=	Intern angle between the ground and the feet attach

So the distance between the two feet should be inferior to 0.83 times the radius of a foot.

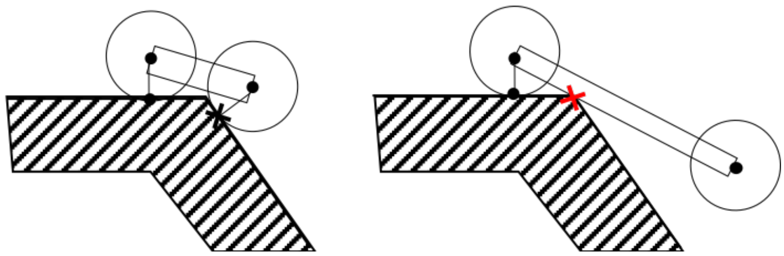


Figure 3.9: Schematic representation of the impact of the distance between the feet on the maximum reachable angle.

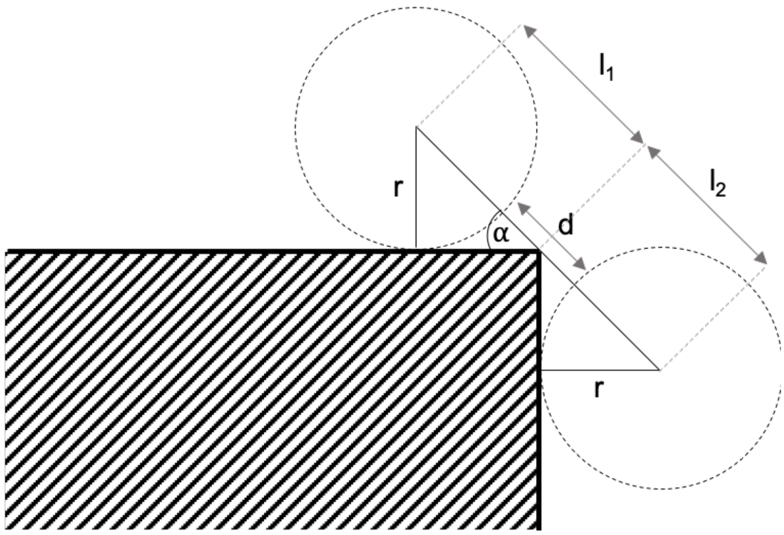


Figure 3.10: Schematic representation of the parameters used to determine the optimal distance between the two feet.

We precociously selected the distance between the feet of the simulated robot so that it can go over a ramp, but in fact, the real robot is much more limited in its movement. Indeed, it can hardly go over a terrain with an angle superior to 180°. It was easier in our simulator to avoid this constraint, but if the objective is to reproduce the observed behavior with the real robot, it may be necessary to think about constraining the terrain to curved angles instead of sharp ones. Alternatively, we may choose to directly add this constraint to the simulator, but it would also require adjustment of the angles.

3.3.4 Main difference with ants: traffic and locomotion

The robot specificity is that it is bipedal and thus has a really specific flipping movement. This leads to the position of the robot's feet being determined by the flipping distance. The robot will touch the ground only at a discrete set of positions. This specificity is even more emphasized in the modeled robot. Indeed, the model being totally rigid, there is not even the slightest perturbation in the positions; which could have been introduced by the flexibility and natural deformation of the real robot. In the simulation, the set of positions touching the ground is perfectly defined and predictable as each position corresponds to the previous one plus the flipping distance as shown in Figure 3.11. This has several consequences: the main one is that the trajectory is highly dependant on the initial position. When we look at the real ants, it is clear that they are able to reach any point in the space and so the initial position is not a parameter of importance.

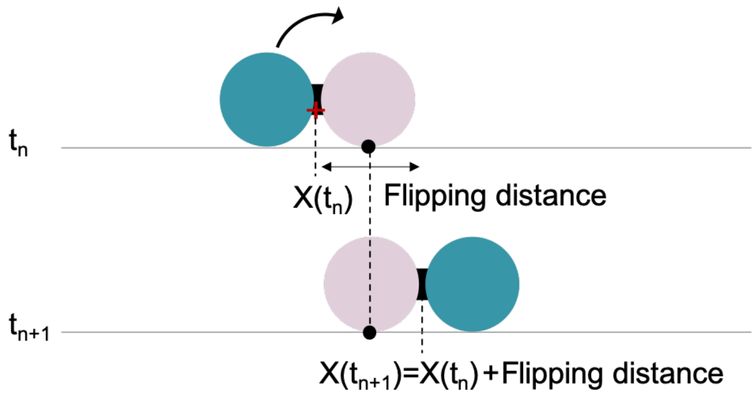


Figure 3.11: Representation of the position of the robot reached at the beginning and at the end of a motion step. t_n correspond to the beginning of the cycle and t_{n+1} the end of this motion step. $x(t_n)$ and $x(t_{n+1})$ are the position of the robot at t_n respectively t_{n+1}.

Another specificity of the robot that has been emphasized in the model is that the locomotion introduces a cycle with a phase parameter. An experiment will not be the same if the robots are not synchronized, i.e. if they are not at the same point of their motion cycle. They can be shifted by a phase or certain angle. This will most certainly change the contact point between robots and lead to totally different results. The ants, having a generally continuous linear displacement, do not introduce any notion of synchronicity or phase shift.

To summarize, the real ant flow can be described by a single parameter: the distance between the ants (that may or may not be constant depending on whether the speed of the ants is the same). This parameter is equivalent to the delay between the ants. In the case of our model, it is more complex because in addition to the delay and the distance between the robots, we introduced two new parameters: the phase shift between the robots and the initial position. Even more importantly, we cannot have a perfect control over both of this parameters at the same time. We can choose to either control distance between robots and phase shift, or delay between robots and initial position. This will be discussed more in details in the next chapter.

3.4 Use of a physics engine

The first step in the creation of the simulator was to assess whether we should use a physics engine and if so how to choose the right one. In order to do so, it was also necessary to determine what was the level of abstraction we were aiming for and thus the physical constraints associated with it.

Considering the level of abstraction of our model compared to the actual physical robot, the choice was to leave aside the friction and a maximum of the physical based features such as damping, springiness or forces. We were aiming to obtain only a kinematic and highly abstract model of the robot. The speed of the different parts are not handled via forces or impulses but simply by reaching a speed target. In addition, the gravity is not used as well, but it is still possible to add it afterward. In our simulation, we will essentially be required to solve a really high number of contacts and create new joints, i.e. solve constraints, at the point of impact. As this requires complex algorithms and iterative solving methods that have already been optimized within most of the physics engine, it became clear that, considering the limited time frame of the project, it would be more effective to use a physics engine even if we will not be using all the physics features.

3.4.1 Choice motivation

The next step was then to determine which physics engine will be the most suitable for the project. The most widely used are generally the 3D ones and several robotics simulators are based on external physics engine. A good amount of them are based on ODE: Open Dynamics Engine [20]. This is the case of Webots[21] that has itself been used to simulate several rigid-body robots such as the Swarm-bot[19] presented in the state of the art chapter, or more recently the lily robots [16] or the Alice robots [22] and many others. Another major robotics simulator, Gazebo, also integrates ODE as its default physics engine. But it still leaves the possibility to use competitors of ODE such as Bullet [23] or more recently Dynamic Animation and Robotics Toolkit (DART), and Simbody. If ODE and Bullet are optimized for maximal coordinate solvers leading to great results for performance over several distinct models, the last two are particularly efficient in case of joint chains. The last 3D physics engine that has to be mentioned is the commercial PhysX [24]. All those physics engines have been compared in terms of dynamic computation, contact solving, predictability of the contact behavior [25] and other aspects in numerous studies [26, 27, 28].

It is tempting to use a wholly integrated robotics simulator such as Webots, but at the time, we were not able to find one using a 2D physics engine. We could have still opted for it if we were sure about the future development of the simulation in 3D, but the current robot hardware will likely not allow for 3D formation, and the 2D efficiency would be severely impacted. Indeed, even if we could have just removed one dimension in the previous robotics simulator/physics engine, the use of the CPU capacity would not be optimized for only 2 dimensions. It appears that using a 3D engine for a 2D simulation is 5 times slower than using directly a 2D physics engine [29]. Thus, as we planned on having a lot of robots (sometime over 50 in large gap with high traffic) interacting and so a high complexity in 2D, we decided to maximize efficiency by opting for a 2D physics engine.

We then had a limited choice between two majors 2D physics engines: Box2D [30] and Chipmunk2 [31]. Chipmunk2 is based on Box2D and so they are quite similar.

Except from the usual preference of programmers towards Box2D, no real studies to compare their efficiency have been conducted, so we mainly relied on implementation details to make our choice. Although both have been ported to several languages, initially Box2D is written in C++ while Chipmunk2 is in C. Another major difference is that Box2D supports continuous collision detection, which is not yet implemented in Chipmunk2. Continuous collision detection [32] can be critical in the case of small and fast objects. Indeed, as a physics engine proceeds by discretizing the time space, it could miss the collision between two relatively thin objects if one is fast enough, leading to a potential tunneling effect or high penetration of one object into the other. To avoid this, continuous collision methods can compute the time of impact and do sub-steps to reach this time step. Nonetheless, it has to be used sparsely as it is more CPU intensive. One of the last major difference between Box2D and Chipmunk2 is that Box2D is tuned to work with real world values (in terms of metrics), which may lead to a better comprehension of the dimensions but has the drawback of being optimized for a limited set of values (between 0.1 and 10m [33]). Chipmunk2 is implemented in term of pixel and has no assumed scale, so it can be more easily tunable.

Regarding the above considerations, we opted for the Box2D physics engine, also motivated by the fact that its developer, Erin Catto, is well known and recognized in the world of computer games.

3.5 Simulator implementation details

Here we will discuss some choices we made regarding the implementation of the simulator. We will go from lower-level details of implementation to higher level ones.

Preamble

We call motion cycle the succession of two step:

- First step: the actual movement of the robot on a flat terrain (to run 180°)
- Second step: the resting period

Dimensions and scale

One specificity of the physics engine Box2D is that it is based on real world metrics. It is optimized to work with m, kg and s. But we would be on the lower extremity of the range of recommended dimensions of objects (between 0.1 and 10m [33]) if we decided to implement the real dimensions of the robot. In addition, our model varies from the actual robot in a way that make the dimension translation difficult. Thus, we decided to make the dimensions relate to our core components as much as possible. The distances will be considered as body-length units and entered as such by the user. This decision is not limited to the space dimensions but applies also to the time dimensions. Indeed, the length of a motion cycle on a flat terrain (moving 180° and resting) has been chosen to be unitary so that all the time constraints applied to the system, such as the experiment duration and the delay in bridge, can be expressed in motion cycle units[1].

[1] If we want to adapt the motion cycle duration in the future, making it no longer unitary, we may want to update the implementation as it is currently not explicitly divided by the motion cycle duration.

Robot phase

Due to its specific cyclic motion, our model introduces a phase parameter. To make the understanding of the behavior and the control over this phase easier, we defined and implemented it so that the angle of the robot on a flat terrain (between o and π) corresponds to its phase in the motion cycle. Therefore the spatial phase matches the temporal one. This is especially beneficial to determine the phase shift between the robots, which is defined as a temporal parameter in our system.

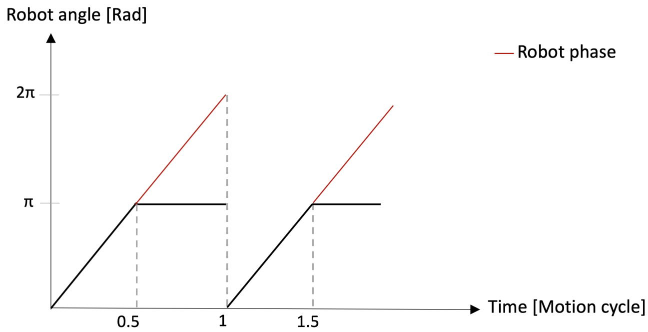


Figure 3.12: Schematic representation of the evolution of the robot angle and the phase of the robot on a flat terrain over a motion cycle

To simplify our parameter space, we fixed the speed and the resting delay of the robot so that the duration of the two steps of the motion cycle (movement+resting) are equal. In addition, to facilitate the definition of the phase, we express the temporal phase as a portion of 2π (i.e. 1 cycle duration = 2π phase and 1/2 cycle duration = π phase). Thus, in our system the temporal phase varies linearly between 0 and 2π. However, the robot angle varies linearly between 0 and π during the actual movement of the robot and then plateaus during the resting period. As the two periods are equal in time, the angle effectively matches the phase during the first half of the cycle.

During the second half of the cycle, the phase does not match the robot angle anymore but corresponds to the time spent in the resting state. It can be expressed as following: (relative to 2π)

$$\phi = (1 + time\ in\ resting\ state/duration\ of\ resting\ state).\pi \tag{3.3}$$

The evolution of the phase and the robot angle are represented in Figure 3.12

How to determine if a robot is stepped over

An important point of the simulation is how we determine that the robot is stepped over without them being aware of the upside orientation. This has to be done during the contact between two robots. We introduced the notion of "contactor" and "contacted". The first represents the robot that initiates the contact while the second represents the one that undergoes it. A robot is considered to be the "contactor" when it contacts while moving and if the contact point is located within the gripping area of its moving wheel.

It is important to notice that the gripper creation and the Bridge state are not necessarily linked in the case where both robots are "contactors". In this specific case, if at least one of them went through the pushing condition (i.e. it moved through an angle of more than 90°), both will enter the Bridge state but only the one that fulfilled this last condition will create the joint (Figure 3.13).

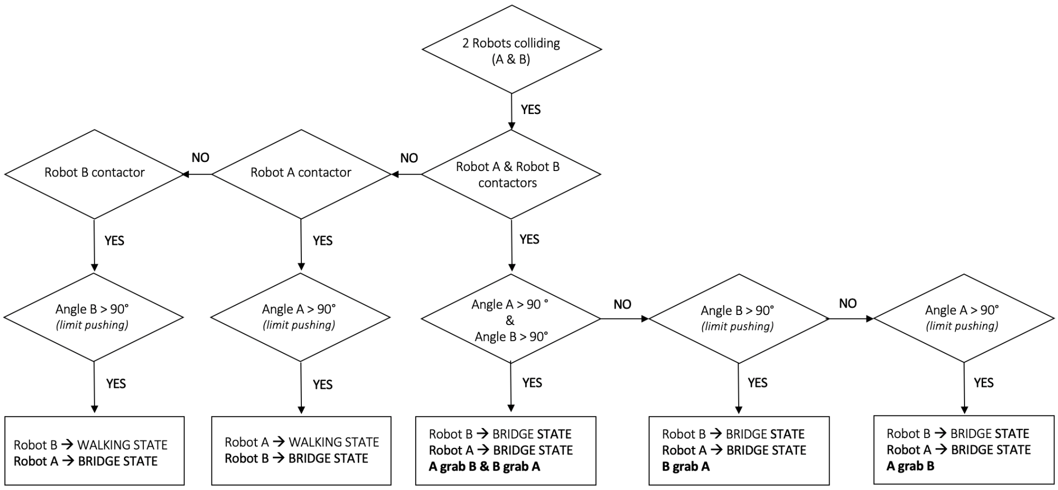


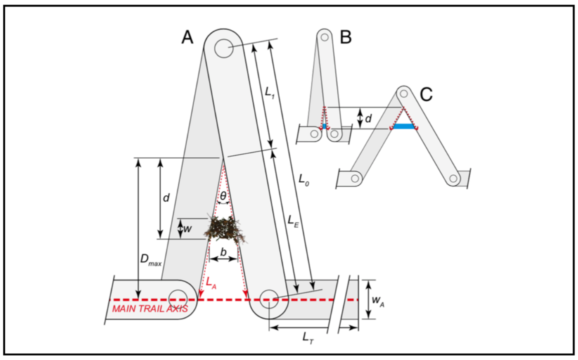
Figure 3.13: Flow chart describing the two robots contact situation. When it does not lead to a state change, no gripper is created.

Chapter 4 Parameters of influence and metrics

4.1 Terrain choice

Most of the experiments are done with a V-shape terrain. This choice is motivated by two main reasons. The first one is that, the prior literature discussed in section 2.1 studied the army ant bridge formation using a V-shape apparatus in their experiments with real ants (see Figure 4.1). Thus, not only we will have a better understanding of what we should expect regarding the results, but it will also be easier to compare with their results. The second reason relies on the observation that most of the time, a bridge starts where a ant's size matches the width of the gap or the hole. So we needed to have a shape where the gap width would increase but also where a certain point would still be no larger than a robot's size. The most straightforward shape that fulfill those requirements in 2D is indeed a V-shape.

(a) Source: Optimal construction of army ant living bridges, Graham and al. (2017) [13]



(b) Source: Army ants dynamically adjust living bridges in response to a cost-benefit trade-off, Reid and al. (2015) [6]

Figure 4.1: Experimental set-up used in the prior literature. The authors are using an horizontal V-shape apparatus allowing them to vary the angle to study the army ant bridge formation.

4.2 Parameters of influence

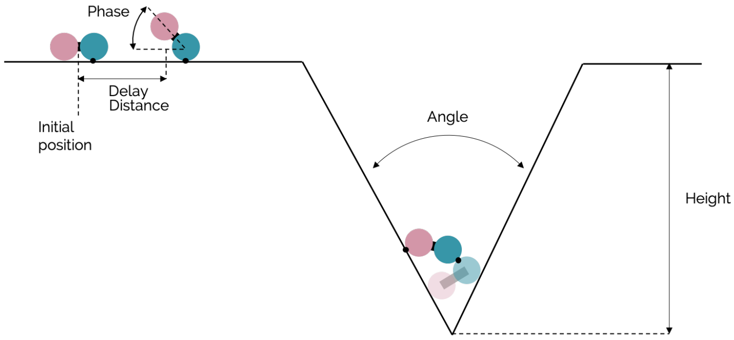


Figure 4.2: Overview of the parameters that have an influence on the final result. The parameters are of two kinds: some describe the geometry of the terrain while the others characterize the traffic of the robots.

4.2.1 Geometric parameters

The geometric parameters describe the terrains and especially the size of the gap on which we want to observe the bridge formation. In our experiments, we will use a V-shape terrain to study the impact of the geometry. As our V is symmetric, only two parameters are required to perfectly describe the geometry: the angle of the V and its height (see Figure. 4.2). In fact, we will use the V-half angle instead of the angle to control the terrain and thus the graphs will be displaying the V half-angle. This is in case we want to implement asymmetric V-gap in the future; the adaptation will be easier if the control is already implemented through the half-angle.

4.2.2 Traffic parameters

As discussed in the section 3.3, our model introduces several traffic parameters that can have an influence on the final result: the distance and delay between the robots, the phase shift between them, and the initial position (shown in Fig. 4.3). Because our model can only go through a set of discrete positions (the robot's feet will always contact the ground in positions spaced by a flipping distance from the previous ones), those parameters are highly dependent one from another, and we can have control only over two of them at the same time. Either we control the pair distance between robots and phase shift or the pair delay between robots and initial position.

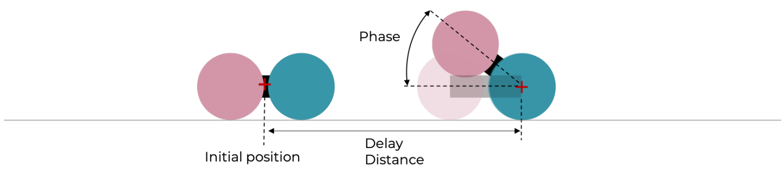


Figure 4.3: Overview of the parameters that describe the traffic of the robot's model. In comparison, the real ant's traffic can be described with a single parameter, either the distance or the delay between two ants.

Delay between robots and initial position

If we chose to control the second pair (delay between robots, initial position), the phase shift and the distance can be deduced from the delay according to the following equations:

$$\Delta\phi = \{\frac{\Delta t}{T}\} * 2\pi \tag{4.1}$$

$$\Delta d = \begin{cases} (\lfloor \frac{\Delta t}{T} \rfloor + \frac{1-cos(\Delta\phi)}{2}) * L_{fp}, & \text{if } \Delta\phi \leq \pi. \\ (\lfloor \frac{\Delta t}{T} \rfloor + 1) * L_{fp}, & \text{otherwise.} \end{cases} \tag{4.2}$$

where:

$\Delta\phi$	=	Phase shift between two successive robots
Δt	=	Delay between two successive robots
T	=	Duration of the whole robot movement (moving + resting)
Δd	=	Distance between two successive robots (taken from the projection of their center on the x-axis)
L_{fp}	=	Flipping distance (i.e. distance ran during a single motion cycle)

Pros:
If the delay is kept constant during the simulation, so will be the phase shift and the distance between robots (at least at the creation; they might be affected afterward by the trajectory and the potential obstacles). Thus the distance and the phase shift can be perfectly predicted, and one can chose the delay value to obtain a targeted distance or phase shift. In addition, this control is easier to implement on a physical robot system, making it possible to compare results from hardware experiments in the future
Cons:
The phase shift and the distance between the robots are dependent one from another. It means that they cannot be fixed to any random value at the same time: either we decide to reach a targeted distance or a targeted phase. Another way to say it is that fixing the distance necessarily fixes phase shift to a given and single possible value (and reciprocally).

Distance between robots and phase shift

If the control of the traffic is done via the (distance between robots, phase) pair, the situation becomes more complex. Indeed to ensure that both the distance and the phase shift between the robots have a targeted value, the robots are not necessarily created at the same initial position. Every robot might have a different initial position within the same single run of the simulator (see Figure. 4.4). The concrete impact is that every robot might also have a different trajectory as the trajectory is determined by the initial position. In addition, the delay between the robots becomes difficult to define and measure as the robots not longer go through the same trajectory.

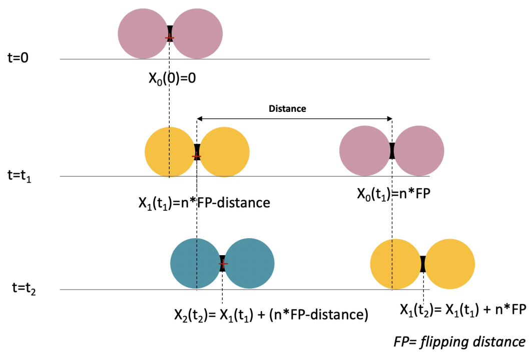


Figure 4.4: Representation of the evolution of the initial position for successive synchronized robots. t_0, t_1 and t_2 successively represent the time stamp corresponding to the creation of a new robot and the end of a motion cycle of the one created before (because they are synchronized). n represents an integer which can be deduced from the closest superior multiple of the flipping distance to the target distance

Pros:
The control of this pair of parameters allows us to choose an exact value for both the distance between the robots and the phase shift. In addition, because it implies that the initial position varies from one robot to another during a same run, it can be seen as the opportunity to test over different initial positions during a single run. Somehow, it may remove the influence of this parameter. This might be only partially true as the sequence of the initial positions might have an impact and, with the previous method, they will not be evenly distributed. The initial position will vary with a given fixed distance (see Figure 4.4).

Cons:
The trajectory vary for every robot during the same run. The initial position will as well and is difficult to determine from the distance and phase shift value. It becomes complex to study the influence of the distance or the phase knowing that we don't have a perfect knowledge and control over some of the other parameters. In addition, few preliminary experiments showed that the difference in the trajectory sometimes led to an increase in the geometric constraints for the robots. A geometric constraint is a locomotion issue where robots become stuck within the terrain which will be further discussed in section 4.3.

Chosen method

Regarding the pros and cons, and especially the fact that controlling the traffic via the delay leads to the robots having all the same trajectory for a single run, we decided to control the traffic with the delay between robots and initial position.

4.3 Metrics

In order to quantitatively analyze the results of our simulation, we decided on specific metrics to describe the bridges formed. We wished to be able to compare the effect of parameters and varied rules on bridge size and stability, as well as the bridge's capacity to adapt and dissolve with the stopping of traffic.

4.3.1 Bridge stability

The first observation was whether a stable bridge was obtained during the simulation. The bridge formation step of a single experiment lasted for 200s i.e. 3min 20s of real time. The analysis confirmed that this duration is sufficient to determine the bridge stability. Indeed, we either observed a stable bridge, no bridges at all or a stacking situation (in which case the formation phase is ended prematurely). If the duration had not been enough, we would have observed bridges that has had not yet reached stability. To assess the bridge stability, a bridge is considered stable once no new robot enters the bridge for at least 40 seconds. As a reference, the robot runs a flipping distance on a flat terrain in 1s (0.5s to do the 180° movement and 0.5s of resting). Thus 40s corresponds more or less to a distance of 40 flipping distances i.e. approximately 20 body lengths. This duration may appear arbitrary, but it allows a robot, that has just been created to go at least to the bottom of the V in the case of the deepest, widest V tested (a V-terrain with a depth of 8 Body-length and an angle of 50°[1]. Some future work might extend this delay a bit, to allow for the time to the robot to go through the entire V instead of just reaching the bottom (in this case 60s should be sufficient).

In addition to a boolean value for bridge stability, the time stamp of the last robot entering the bridge before the stability condition has been met is also stored. This corresponds to the duration to obtain the stable bridge.

4.3.2 Stacking

One case has to be differentiated from the other bridge formation situations: the case where the robots, instead of forming a bridge, are piling up at the entrance side of the V-shape. This situation is detected when a robot enters the bridge state too close to the initial position, i.e. at less than one body length. In this case, no more robots are created as it may lead to a crash of the simulation, and the bridge formation step is prematurely ended to start the dissolution step. A beginning of stacking may be observed but will not lead to an actual detection of the stacking situation detection until a robot actually enters the bridge state close enough to the initial position.

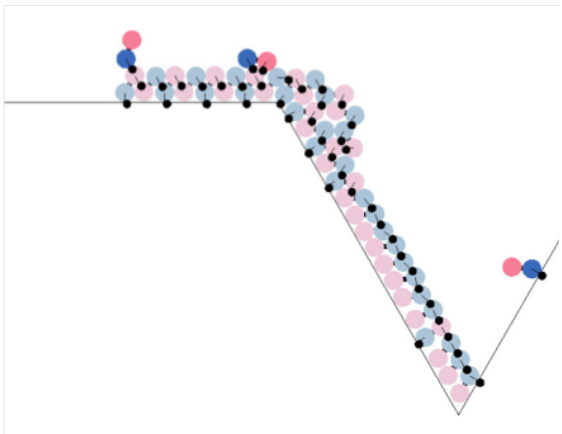


Figure 4.5: An example of a situation considered stacking. The robots are piling up at the entrance of the V-gap.

[1]those dimension of the V-gap correspond to the widest gap, and thus critical one, used in the experiments

4.3.3 Number of robots

As one measure of bridge size, we check the number of robots involved in the final bridge. This number of robots is not only the number of robots in the bridge state but also includes the ones in the walking state that are stuck below the structure. Indeed, this last kind of robot might also have an impact on the dissolution phase.

If this number is difficult to analyze by itself ,due to its relation to other parameters such as the geometry of the terrain, it is required to determine the percentage of dissolution.

4.3.4 Length and height of the bridge

The height of the bridge is taken from the bottom of the obstacle. It is the main quantitative metric that will be studied to determine the eventual bridge formation trends. In order to determine the height of the bridge, all the positions of the robots in the final bridge are compared and used to approximate the bridge shape. In the case of the V-terrain, the left side of the structure is considered to be the most to the left point between all the robots feet or ideally grippers. If this point is more to the left than the actual top left corner of the V, the left height is set to this last coordinate. The same reasoning is done for the right side of the bridge. Usually the final approximation seems to match sufficiently the bridge as it can be seen on Figure 4.6

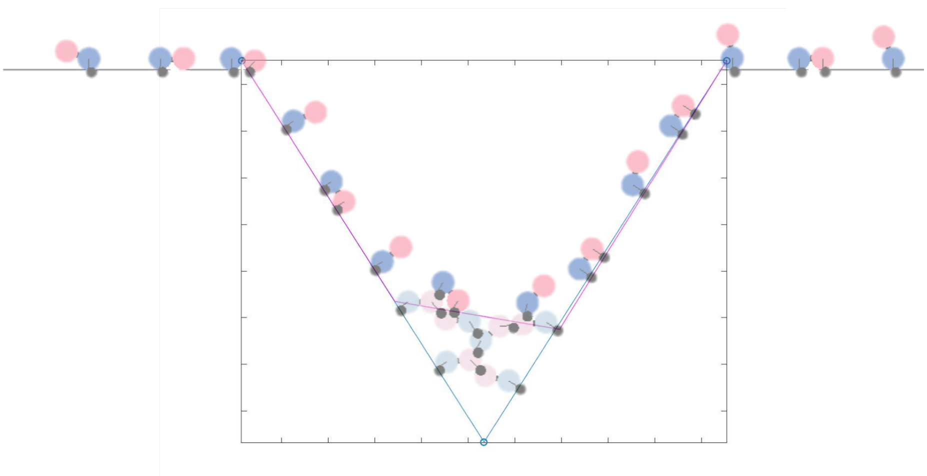


Figure 4.6: Approximation of the bridge shape (in magenta) obtained from an experiment.

In the results presented in chapter 5, generally the mean bridge height is evaluated. This corresponds to the average between the right and the left height of the bridge. In the more specific case of a really high traffic, sometimes the height at the middle of the bridge will be preferred. It will be more representative of the shape as it will give less importance to the stacking of the robots compared to the mean height.

4.3.5 Bridge dissolution

The dissolution step starts at the end of the formation phase and has the same duration of 200 iterations (3min 20s at 60 FPS). During this step, no more robots are created (i.e. the traffic is set to 0). After the last robots have passed over the bridge, the bridge state robots will begin to leave the bridge state and the bridge will dissolve.Dissolution is considered successful if all of the robots manage to leave. However, instead of just outputting a binary result: either total dissolution or not, the percentage of dissolution is calculated using the number of robots in the bridge at the start and end of dissolution. In addition, when the dissolution is reached, the time required to do so is saved.

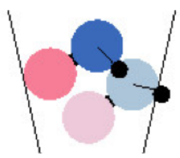
4.3.6 Dissolution failure causes

In an attempt to understand better the dissolution issues, we classified the causes of failed dissolution into four categories:

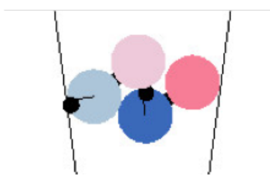
- Geometric constraint: the robot is not stepped over and had detached the right wheel to start to move, but it is stuck because of the geometry of the V or the current structure of the bridge.
- Up-grab: a robot from below is grabbing the one from above.
- Double-grab: both robots are grabbing each other
- Repetitive pattern: a robot below the bridge is stuck and repeats the same trajectory again and again. This robot goes through the same contact points and one of them is a robot above; thus not letting the robot from above the time to leave the bridge state.

However, some situations might be difficult to classify in solely one of the above as several causes can be found at the same time.

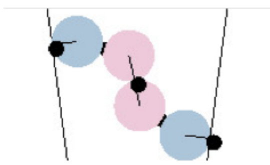
The situations are summarized in the figure below (Figure 4.7).



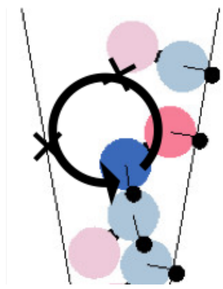
(a) Geometric



(b) Up-grab



(c) Double-grab



(d) Repetitve pattern

Figure 4.7: Potential causes of dissolution failure

Chapter 5 Experimental results

5.1 Hypothesis

The first expectation is that some situations lead to bridge formation and that these bridges are able to self-stabilize. Once the traffic is stopped, the bridge should be able to self-dissolve. In addition, the bridge formation should be dependent on some geometrical factor such as the angle of the V and its depth as well as the traffic density. If we compare our simulation with the experiments conducted by Jason M. Graham and al. [13] (discussed in chapter 2), we can even go further. Although their experiments are conducted in the horizontal plane whereas our simulation takes place in the virtual vertical one, we might expect similar behaviors. The height of the bridge should still increase when the angle decreases and when the traffic increases.

Setup differences The first and major difference is due to the specificity of our model: contrary to the real ants, our robot can only reach a set of discrete positions that are determined by the flipping distance (section 3.3). Thus the ant density is not the only traffic parameter that will impact the results, the initial position has to be considered as well. In fact more than just the initial position, it is the initial distance of the robot from the bottom of the V that is of importance as this parameter will participate in the determination of the first point of impact. One can suggest that the result should stay the same in terms of bridge height and number of robot involved, when we vary the bridge depth while keeping the initial distance from the bottom of the V constant.

In fact, it is more complex as the same impact on the trajectory happens if we modify the length of first slope. Thus, the result should stay the same only if, in addition to keeping the initial distance fixed, we vary the depth so that the length of the first slope always varies by a multiple of the flipping distance.

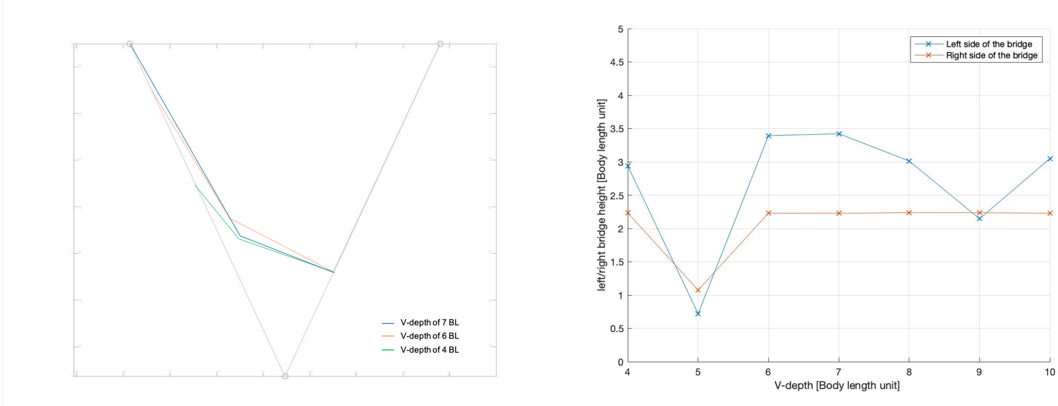


Figure 5.1: Difference between the left height h_l and the right height h_r of the bridge as a function of the robot traffic. The traffic is defined as the inverse of the distance between the robots. The points represent the finale height difference obtained for different depth of the V-shape [7, 8, 10, 12, 15, 20]. The orange line is the mean value of this difference over the angle.

The second main difference is that the V-shape is in the horizontal position in the experiments with the real ants, whereas in our simulator it is in the vertical orientation. Nonetheless, we believe that the evolution depending on the parameters should be similar. However, because we are not working in 3D, the robots have no way to leave the bridge from below. Thus, the bridge will not "migrate" until a certain height as in the articles but "grow" until a certain height.

At last, in the discussed articles, they use a given apparatus with a fixed size of the platforms. It comes that, when the angle of the apparatus is changed, the effective depth of the bridge change consequently as the junction between the two platforms goes up. In our experiments, we decided to keep the V-depth fixed instead of the first slope length.

5.2 Fixed delay between the robots

5.2.1 Setup

Each experiment is composed of 2 steps: a bridge formation phase and a bridge dissolution one. They both last for 200s i.e. 3min 20s of real time. During the bridge formation step, the robot are created with a given traffic controlled by the pairs delay and initial position. In case the robots are stacking up (see criteria in section 4.3), the formation step is ended prematurely and the simulation goes on with the dissolution step. When the formation step is done, the simulator starts the dissolution phase by stopping suddenly the traffic of the robots.

Regarding the search space: it has been consequently reduced. The V depth is fixed to 8 Body lengths units for all experiments and the initial position fixed to an arbitrary value.

What we call a "set of experiments" is composed of a single run of the simulation for every value of the pair: traffic, V half-angle. Within a single set, every run as the same phase shift between the robots, independently from the traffic value. To do so, the delay is varied, between 2 runs, with a constant step of 1 s which corresponds to the motion cycle duration on a flat terrain (movement time plus resting time). However, within a single experiment, this delay between two successive robots is invariant.

The range of the parameters tested in a set of experiments is the following:

- The delay is varied between 2.5s and 6.5s with a 1s step[1]. It corresponds to a variation of the distance between 1.5 Body lengths and 3.5 Body lengths with a 0.5 Body lengths step.
- The half-angle of the V varies from 7.5° to 50° with a step of 2.5°.

Several set of experiments are done with different phase shifts: 0 (synchronized), $\frac{\pi}{2}$, π, and $\frac{3\pi}{2}$. The corresponding situations are represented on Figure 5.2.

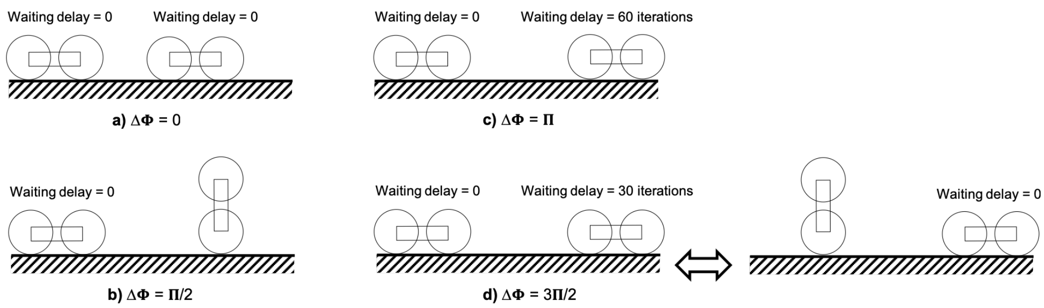


Figure 5.2: Representation of the different phase shifts between the robots

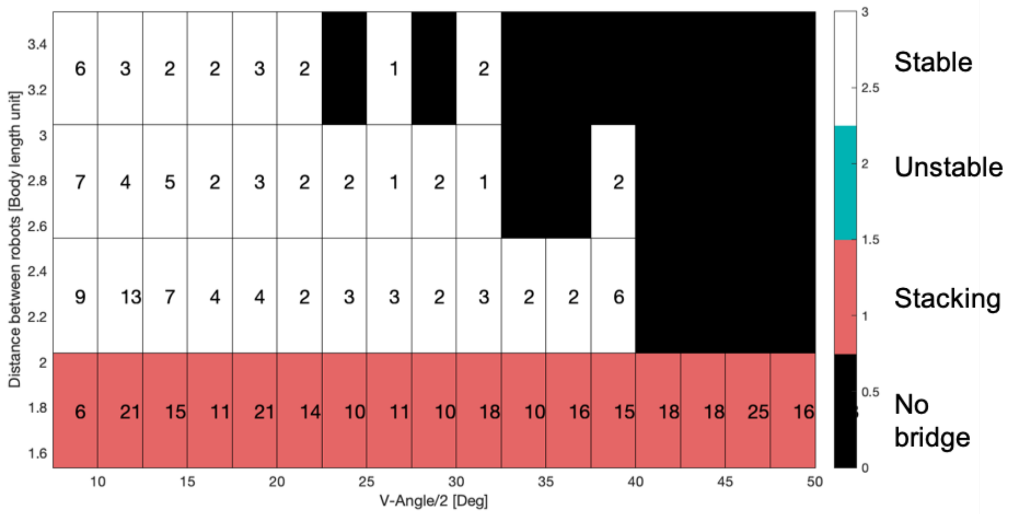
5.2.2 Stability and Dissolution

In parallel to the overall stability and dissolution results, we wanted to test different behaviors/flexibility levels for the robots in the bridge state. To do so we compared the results obtained with a fixed rotation in bridge state with the one obtained with a limited rotation of ±30°. In this first situation, the structure cannot move at all while in the second one, it is able to deform a bit.

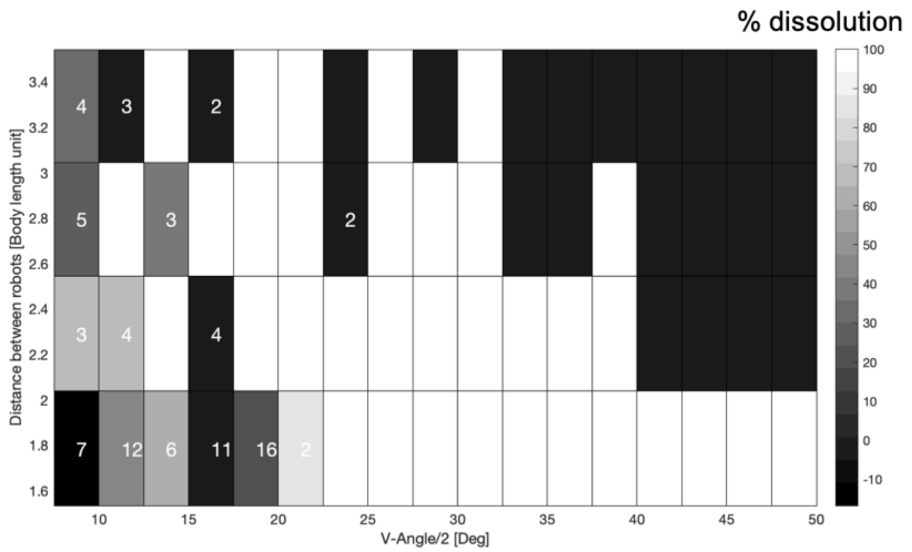
The comparison is done with a fixed phase shift of π i.e. 180°.

[1]In fact, this value is for a phase shift of π between the robots, for other values of the phase shift it changes slightly as does the distance between the robots

Fixed rotation in bridge state



(a) Stability of the final bridge depending on the traffic expressed as the distance between robots (vertical axis) and the half-angle of the V (horizontal axis). The numbers on the meshgrid represent the number of robots involved in the bridge.



(b) Percentage of dissolution at the end of the simulation depending on the traffic expressed as the distance between robots (vertical axis) and the half-angle of the V (horizontal axis). The darker is the bin, the less the bridge has dissolved. The numbers represent the number of robots stuck in the bridges at the end of the simulation.

Figure 5.3: Bridge stabilization and dissolution results for a set of experiments controlled via the delay with a phase shift of π and the movement blocked in bridge state.

The first observation (Figure 5.3) is that there are only 3 different situations: stacking, stable bridge or no bridge. The bridges are formed for a higher value of the traffic and a lower value of the V-angle.

Regarding the dissolution, it appears to be less robust for a lower value of the angle.

Once we analyze the situations where the dissolution is not total we can classify the failures into the four categories (section A.2): up-grab, geometric constraint, double-grab or repetitive pattern (see section 4.3 for details). We obtain the following proportion:

Up-grab	**Double-grab**	**Geometric constraint**	**Repetitive pattern**	**Total dissolution**
$\frac{5}{17} \approx 29\%$	$\frac{3}{17} \approx 18\%$	$\frac{10}{17} \approx 59\%$	$\frac{1}{17} \approx 6\%$	$\frac{39}{56} \approx 69.6\%$

The geometric constraint is the cause of more than half the dissolution issues.

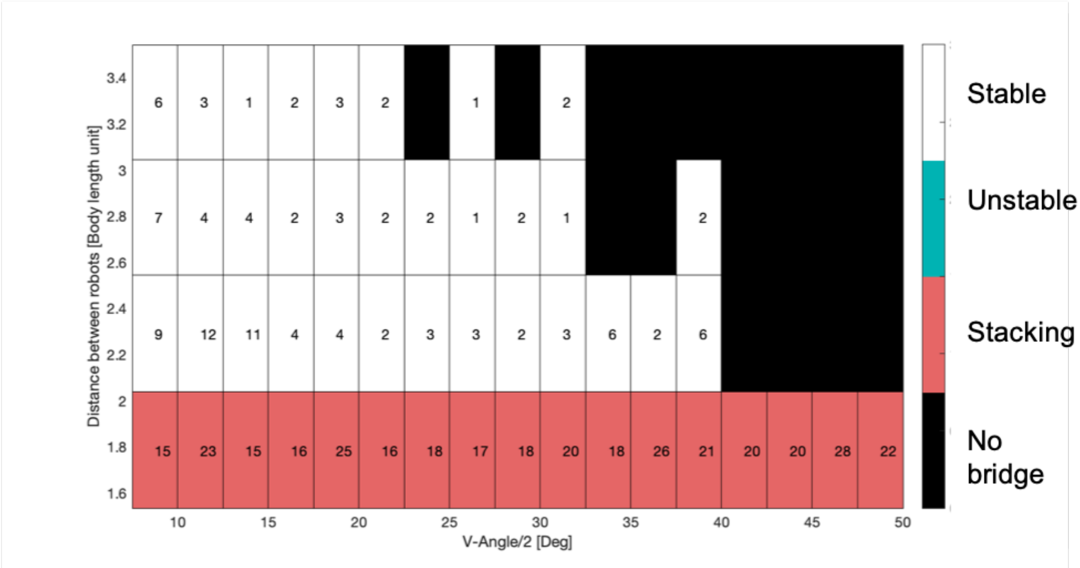
Limited rotation in bridge state

Our hypothesis is that adding some springiness to the model is a way to reduce the number of geometric constraints. An intermediary solution (compared to adding springiness in the internal joints of the robot) is to add a bit of flexibility in the movement of the robots in the bridge state. Instead of blocking the rotation of the joints of the feet in the bridge state, it is now only limited to a given angle. This angle has been chosen to be $\pm 30°$[2]. It leads to the following results:

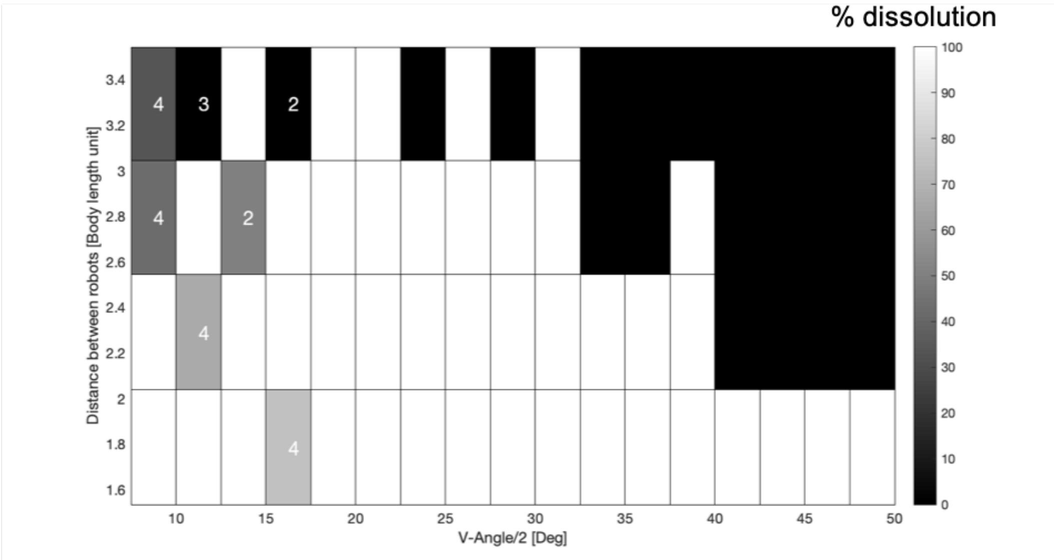
Up-grab	**Double-grab**	**Geometric constraint**	**Repetitive pattern**	**Total dissolution**
$\frac{2}{10} = 20\%$	$\frac{3}{10} = 30\%$	$\frac{4}{10} = 40\%$	$\frac{2}{10} = 20\%$	$\frac{46}{56} \approx 82.1\%$

Not only the proportion of geometric constraints leading to partial dissolution has been reduced, but the overall proportion of total dissolution is also improved, from 69.6% when the feet joints are totally blocked in the bridge mode, to 82.1% when the rotation is allowed and only limited. In addition, one could have feared that it might impact the bridge formation, leading to rocking and bouncing structure as it has been observed in preliminary experiments with totally free rotation. But the results are quite similar (see Figure. 5.4): there is no additional bridge formation and, once the results have been studied independently, the bridges' structure are still stable (section A.1). Even when the results show a different number of robot involved in the finale bridge compared to the previous experiments. In fact, when the stacking situation is not considered, only 5 over 51 experiments have different results or only $\sim 10\%$ of the results are different.

[2] it corresponds to the angle of the physical robot, attached on one foot, under the load of the gravity



(a) Stability of the final bridge depending on the traffic expressed as the distance between robots (vertical axis) and the half-angle of the V (horizontal axis). The numbers on the meshgrid represent the number of robots involved in the bridge.



(b) Percentage of dissolution at the end of the simulation depending on the traffic expressed as the distance between robots (vertical axis) and the half-angle of the V (horizontal axis). The darker is the bin, the less the bridge has dissolved. The numbers represent the number of robots stuck in the bridges at the end of the simulation.

Figure 5.4: Bridge stabilization and dissolution results for a set of experiments controlled via the delay with a phase shift of π and the movement limited between $\pm 30°$ in bridge state.

The previous results justify the adoption of the $+/-30°$ limit of the movement in the bridge state. This constraint will be used in the next set of experiments.

5.2.3 Impact of the V half-angle on the bridge height

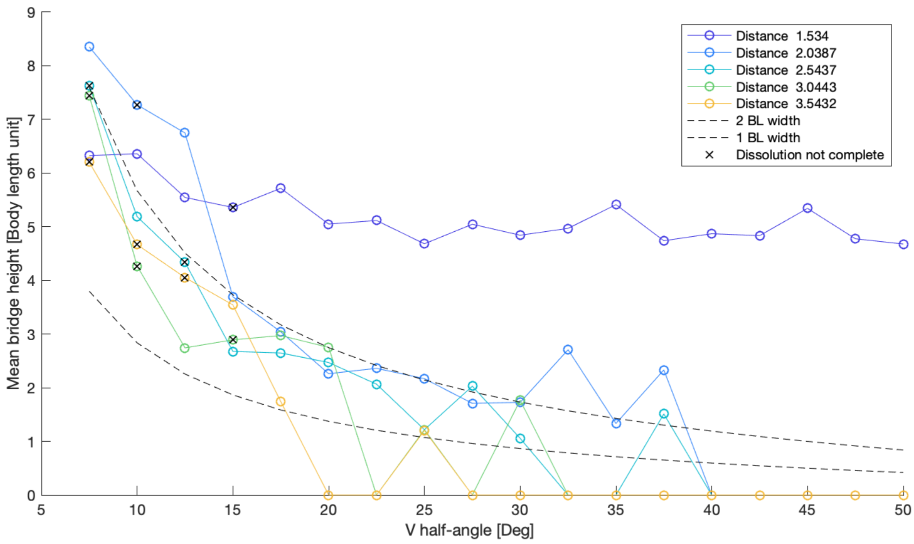


Figure 5.5: Evolution of the mean bridge height as a function of the V half-angle when the traffic is fixed. The dash-lines represent the height which corresponds to a width of the V-shape of 2 Body lengths units and 1 Body length unit. This set of experiments has been done with a constant phase shift of π. Each curve represents a different value of the traffic expressed as the distance between two consecutive robots.

For a precise traffic value (2.5s i.e. 1.5 Body lengths), the pile-up of the robots (stacking) happens whatever the angle value is. It leads to an almost constant bridge height which is inferior to the total V-shape depth (see Figure 5.5). Indeed, the height considered correspond to the average between the right and left side of the V (section 4.3) and when the pile up happens it doesn't have the time to grow on the right side. When no pile up is observed, apart for a few exception, the bridge height stays in between the height that corresponds to a 1 Body length width and the one that corresponds to a 2 Body lengths width. In fact, the bridge created act as a suppressor of collision. Instead of reducing significantly the actual travelled path, it only suppress the congestion.

5.2.4 Influence of the delay between robots

When the delay is varied while keeping the phase shift constant, it can be observed that the delay acts more like a on/off switch on the bridge formation. In fact, it's not exactly a binary result: a stable bridge or no bridge at all. For a given angle, the bridge height stays similar for a certain range of traffic. Outside this range, when the traffic is higher (lower delay/distance), it leads to stacking situation. When the traffic is lower, no bridges are formed at all. This specific range is dependent on the angle value: it is wider when the angle is smaller and reduces to become empty when the half-angle is increased above 40°. However, the stacking limit is kept constant whatever the angle value is and corresponds to $\sim$ 1.5 Body lengths unit or 3 time the flipping distance.

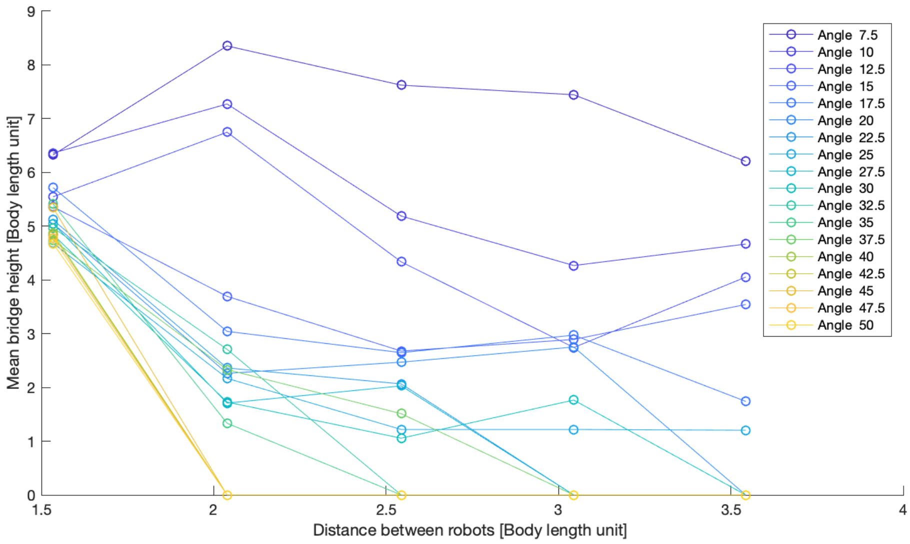
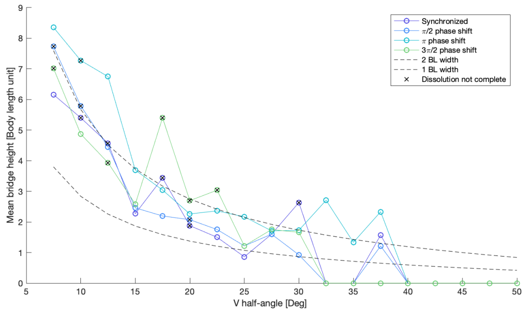


Figure 5.6: Evolution of the mean bridge height as a function of the traffic (expressed as the distance between robots) when the V-half angle is fixed. Each curve represent a different value of the V half-angle

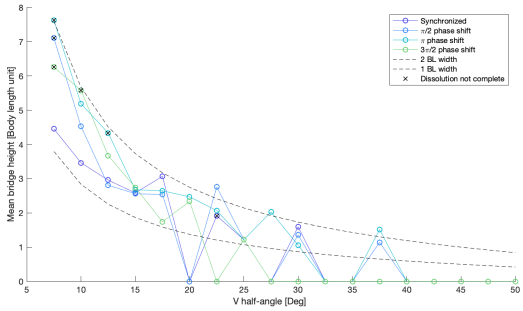
It can be seen in Figure 5.6 that indeed this distance leads to a higher bridge for all the angles. Afterward, when the half-angle is sufficient (above 15°) the bridge's height decrease and plateaus. For a really small angle the height stays around the pile-up height as the top of the V corresponds more or less to the width of to Body length. Above a certain angle no bridge form when there is no piling-up of the robots.

5.2.5 Influence of the phase shift between robots

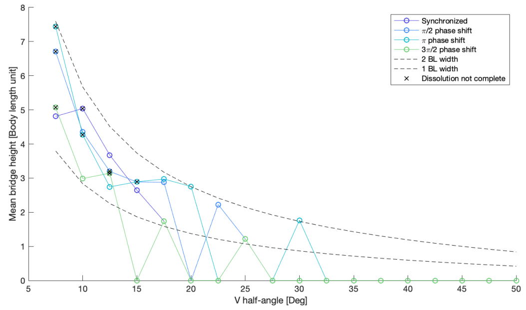
In the previous experiments, all the run were done with a fixed value of the phase shift equal to π. In the following paragraph, the impact of the phase shift will be discussed, by conducting different sets of experiments with different phase shift values.



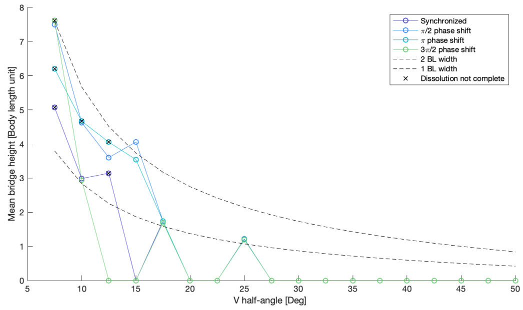
(a) Delay between the robots of respectively 3, 3.25, 2.5, 2.75 i.e. a distance from 1.5BL to 2BL



(b) Delay between the robots of respectively 4, 4.25, 4.5, 4.75 i.e. a distance from 2BL to 2.5BL



(c) Delay between the robots of respectively 5, 5.25, 5.5, 5.75 i.e. a distance from 2.5BL to 3BL



(d) Delay between the robots of respectively 6, 6.25, 6.5, 6.75 i.e. a distance from 3BL to 3.5BL

Figure 5.7: Evolution of the mean bridge height as a function of the V-half angle for different phase shifts between the robots.

As expected, the results are not the same depending on the phase difference between two successive robots (Figure 5.7). Nonetheless, they all seem to follow the same trend for a given traffic value. However, because the results are slightly varying depending on the phase shift, the question rises of how a perturbation in this phase shift within a single run will impact the results. This question is even more relevant considering the fact that the real ant flow is never perfectly constant. Thus, the next batch of experiments will be done by adding a perturbation in the delay between the robots.

5.3 Gaussian delay between the robots

5.3.1 Setup

In the nature, the real army ant traffic is never perfectly constant. Thus, it is necessary to see how the simulation will adapt if some perturbation is introduced into the ant traffic. To add this perturbation, the delay between each robot will be determined following a Gaussian distribution. The parameters of the Gaussian have been chosen so that the delay variation does not induce too much variation in the distance between the robots, but essentially impact the phase shift. The experiments will still be done for different traffic value, which will correspond to different mean of the Gaussian. But the distributions, whatever the traffic value is, will always be centered on a phase shift of $\pi/2$ and a standard deviation of $\pi/2$ (Figure 5.8). It means that for a single run, 68%

of the robots' delay will lead to a phase shift comprised between 0 and π and 95% to a phase comprised between $-\pi/2$ and $3\pi/2$.

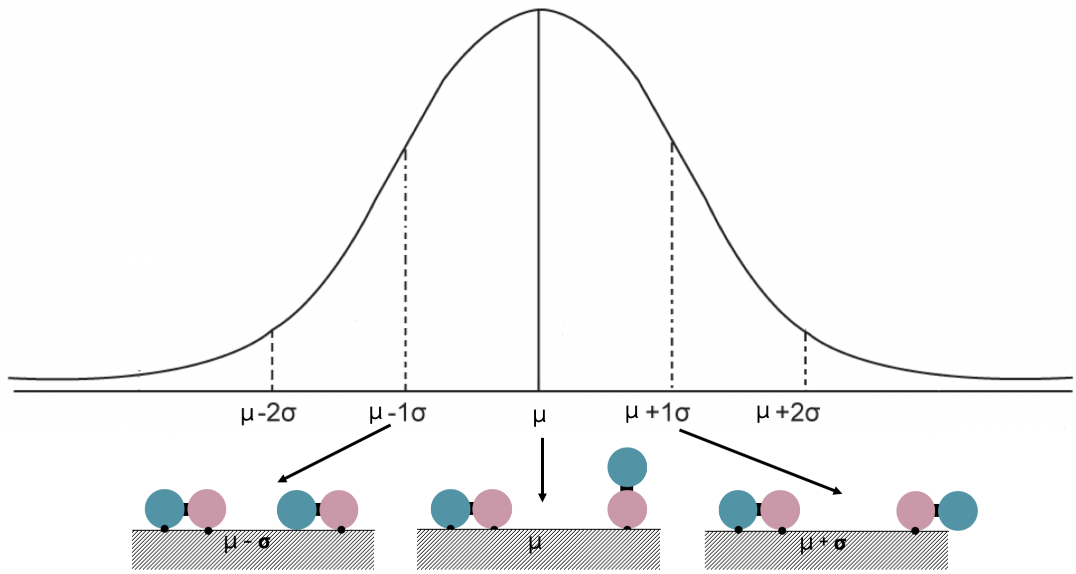
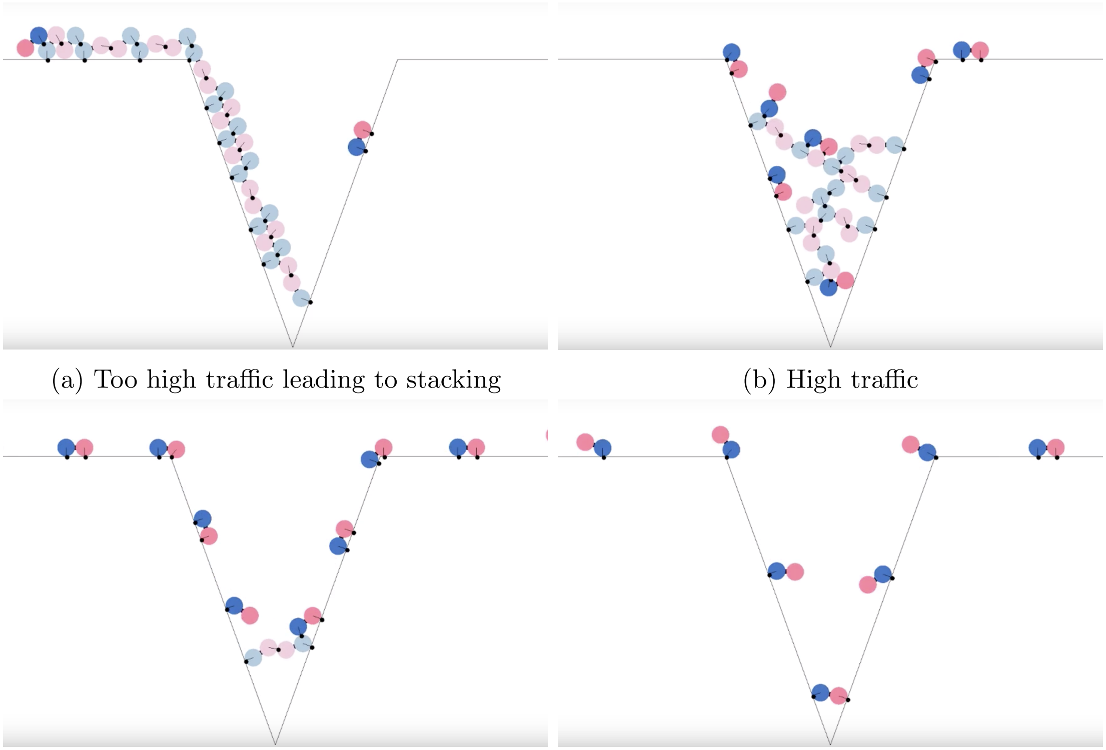


Figure 5.8: Representation of the parameters of the gaussian distribution of the delay.

10 different sets[3] of experiments have been run. As for the previous experiments, a single run is composed by two phase: a bridge formation one where the robots are added following the Gaussian delay and a bridge dissolution step where no more robots are created. This second step has just been extended slightly (from 200s to 300s) to make sure all the robots have the time to get out of the bridge.

[3] a set is composed of a single experiment for every pair of value V-half-angle and traffic

5.3.2 Bridge formation



(a) Too high traffic leading to stacking

(b) High traffic

(c) Medium traffic

(d) Low traffic, no bridge is formed.

Figure 5.9: Different final bridges obtained with the simulation. The V-shape has a depth of 8 Body lengths and the half-angle is fixed to 20° for all the above experiments. The delay between robots follow a Gaussian distribution that has been generated with the same seed. Each image is obtained with a different value for the mean of the Gaussian distribution. From left to right, top to bottom: (2.25s, 3.25s, 4.25s, 8.25s) which correspond to distances of respectively (1.3 BL, 1.8 BL, 2.3 BL, 4.3 BL).

Regarding the number of stable bridges and the parameters (V-half-angle, traffic) that lead to it, the results are not significantly different from the previous experiments. There is a constant core of stable bridges observed for a low angle - high traffic (i.e short distance) set of parameters (see Figure 5.10). The stacking of the robots is still observed for a really high traffic value, which corresponds to a mean distance between the robots of ~ 1.3 Body length. At the frontier between where a stable bridge forms and no bridge forms at all, the bridge formation is less robust as not all the experiments lead to a bridge formation. The bridge formation is stochastically determined. This is potentially due to the distribution of the Gaussian delays during a single run that may be more or less on the side of a larger distance. Or maybe the sequence of the robot's delay has a non negligible impact.

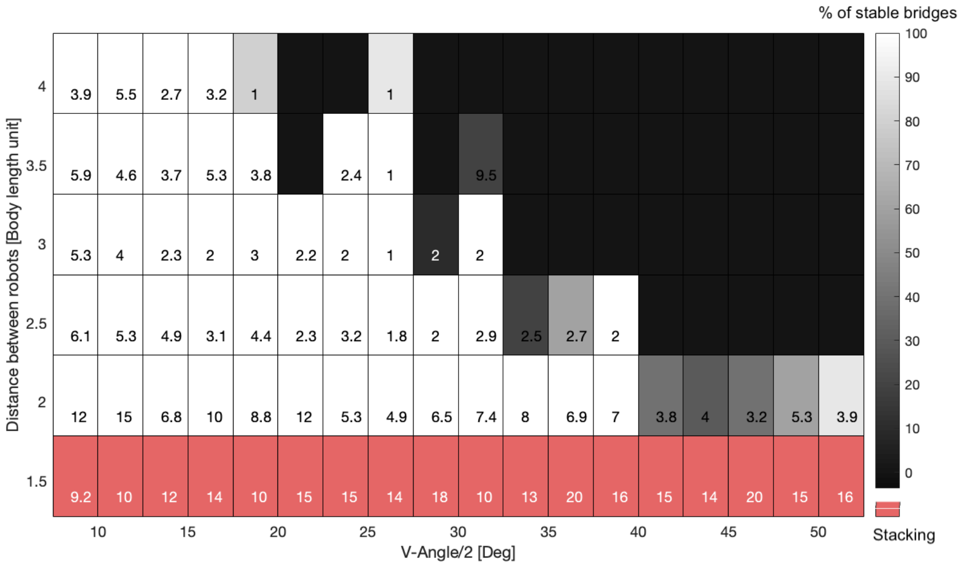


Figure 5.10: Bridge stability results averaged over 10 set of experiments where the delay/distance between robots follow a Gaussian distribution. The gray gradient represent the percentage of observed stable bridge over the 10 sets. In a general way, we observed only stable bridge or no bridge at all. Black and no number means that no bridge has been observed. Red signifies a stacking situation. On the horizontal axis is the V-half angle and on the vertical, the traffic expressed as the mean distance between two consecutive robots. The number in the cells is the average number of robots involved in the bridge when one is formed.

5.3.3 Bridge height

Looking at the actual height of the bridges formed, an additional situation, that seemed not to exist when using a fixed delay, can be observed (Figure. 5.11). In fact, when the mean delay (3.5s which corresponds to a 1.8 Body lengths distance) is close to the stacking delay (2.5s which corresponds to a distance of 1.3 Body lengths), the robots form a bridge higher than the 2 Body lengths trend usually observed. When the delay is increased above this value (i.e. the traffic is reduced), the bridge height tends to go back to follow the 2 Body lengths trend. This is indeed visible on the simulation results Figure 5.9.

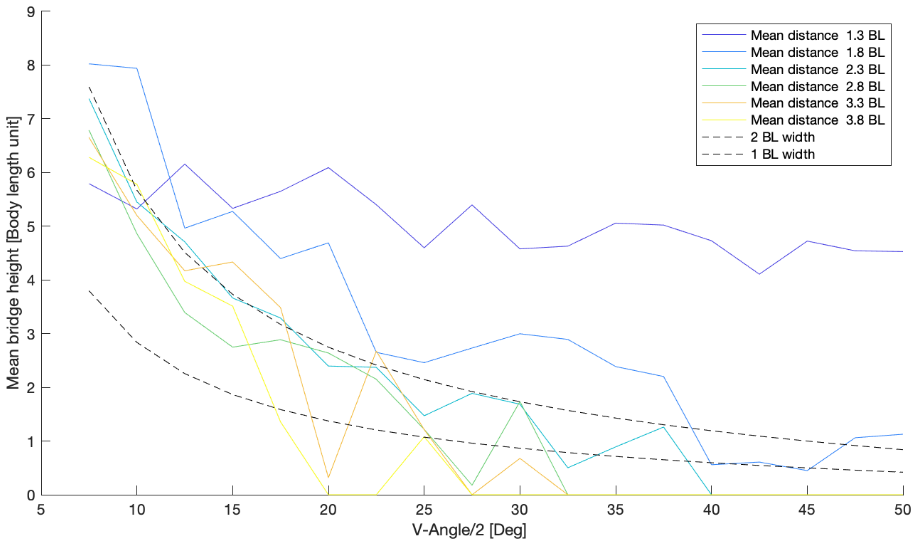


Figure 5.11: Bridge height averaged over 10 set of experiments with the delay between the robots following a Gaussian distribution. The height is expressed as a function of the V-half angle. Each curve represent a different mean traffic value expressed as the mean distance between two successive robots.

However, one might be surprised by the sudden crash observed in the curves in Figure 5.11 observed, for example, at a half-angle of 20° for a higher value of the traffic (3.3 Body lengths and 3.8 Body lengths). To verify if this phenomenon is systematic, we computed the variation of the bridge height over the 10 sets of experiments, shown in Figure 5.12. It appears that all of them except one do not form bridge at 27.5° and a traffic characterized by a distance between robots of 3.3 Body lengths and 3.8 Body lengths. This phenomenon is not present for a higher traffic (lower distance). A possible explanation is that the trajectory might be different from the trajectories obtained with the other angle and so are the positions of contact. Indeed because it is the V-depth that is kept constant and not the length of one of the V arm, the distance from the top entrance corner to the bottom of the V varies with the angle. Thus, although the initial position is the same for the different angle, the actual distance from the initial position to the bottom of the V varies and so does the position where the closer contact to the bottom will happen.

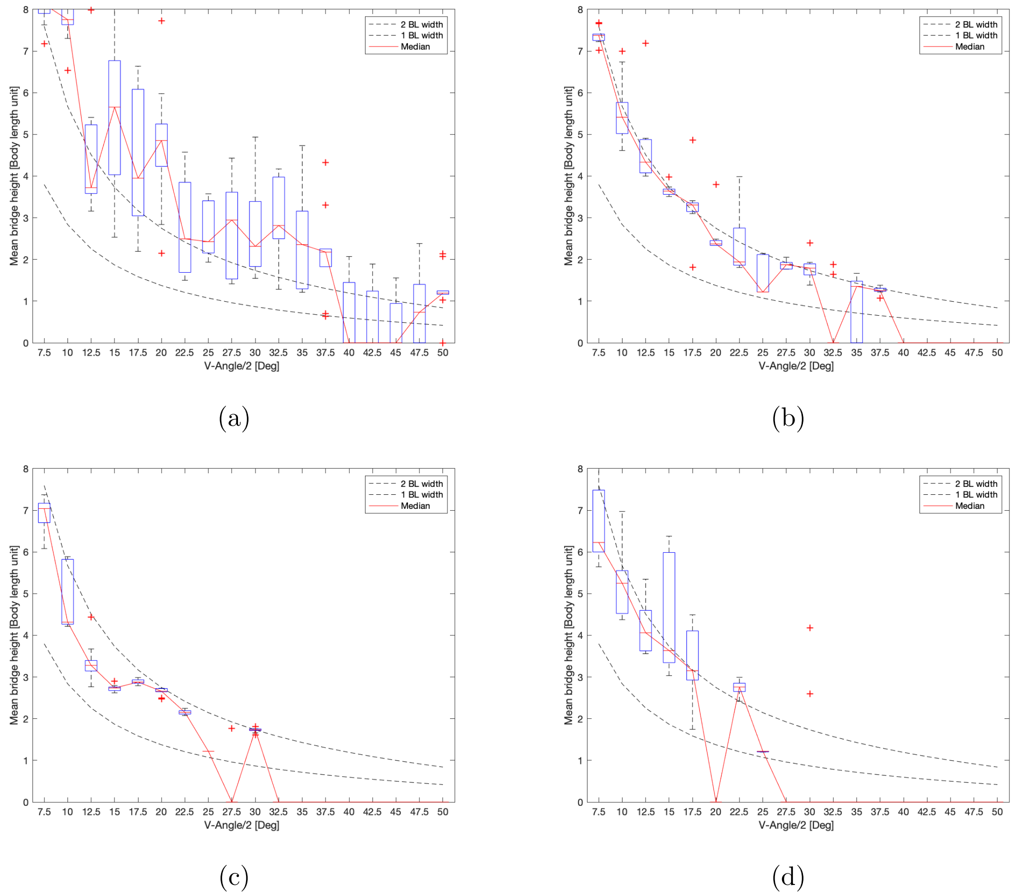


Figure 5.12: Distribution of the bridge height for the 10 experiments with a Gaussian delay between the robots depending on the V half angle and for different traffic values.

Going back to the exception of the high traffic (centered around a delay of 3.5s), we observe that this is also where the variability between the 10 experiments is the highest (Figure 5.12). Because the difference between the successive experiments is in the exact value of the delays generated by the Gaussian distribution, but also in how they follow one another, this observation suggests that the sequence of delays also matters.

When looking closer at the individual experiments it appears that the bridge is formed higher without observing a stacking situation. In fact a few portion of the robots are still piling up at the entrance of the V-gap but not to the critical point where they would enter the bridge state out of the gap. The bridge height seems to be really dependant on this proportion of really close robots that varies every time we launch the experiment due to the intrinsic randomness of the Gaussian.

This phenomena happens only for this specific value of the traffic because the Gaussian is centered on the critical delay: at the edge between stacking and the 2 Body lengths trend. Thus, it introduces both robots doomed to pile up and others just far away enough to avoid this phenomena. The first kind of robots will then starts a new nucleus whose rising will be controlled by the sudden spacing in the ant flow due to the introduction of robots with a larger delay. It rises the question of whether a control on the bridge height can be obtained by changing the proportion of robots doomed to piles up introduced into the system. Our hypothesis is that doing so by increasing the standard deviation of the Gaussian delay distribution, and thus, increasing the probability of introducing closer robots would indeed increase the actual bridge height. This hypothesis is discussed in the next paragraph.

5.3.4 Varying the standard deviation in the case of a high traffic

We tested our hypothesis -*that it is possible to influence the final bridge height by changing the proportion of robots doomed to piles up introduced into the system*-, by changing the standard deviation of the Gaussian delay distribution. We ran a new batch of experiments with the same setup but only the 3.5s delay value (1.8 Body lengths distance) and different standard deviation for the delay distribution: 0.1s that corresponds to $\pi/5 = 36°$ phase shift, 0.25s that corresponds to the previous $\pi/2 = 90°$ and finally 0.4s that corresponds to $4\pi/5 = 144°$ (the choice of the value is arbitrary.). The results (see Figure 5.13) tend to confirm the hypothesis. However, when the standard deviation is augmented, it increases the final height of the bridge but it also increases the chance to observe a stacking situation.

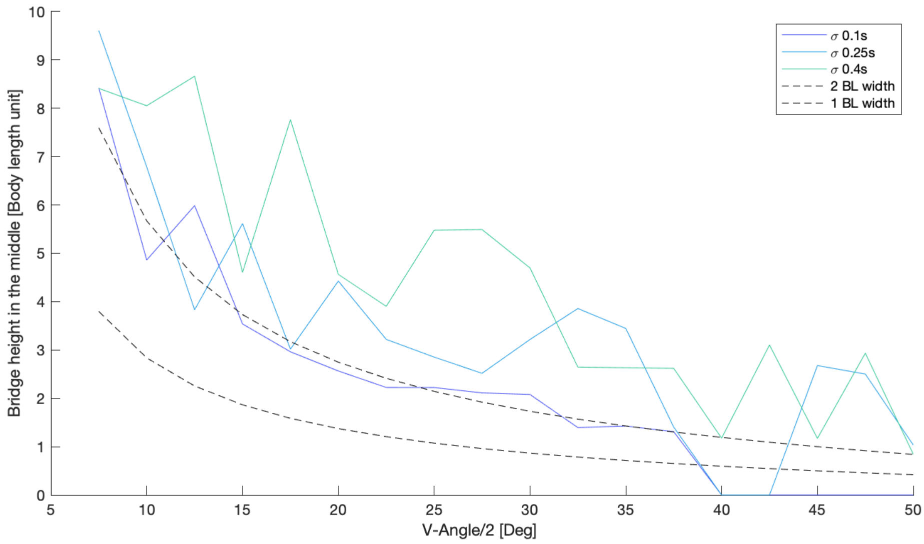


Figure 5.13: Final mean bridge height as a function of the V-half-angle for different Gaussian distribution of the delay. The three distinct Gaussians distribution are all centered on a delay of 3.5s (i.e. a distance of 1.8 Body lengths and a phase shift of 90°) but the standard deviation are respectively 0.1s (36° of phase shift), 0.25s (90° of phase shift) and 0.4s (144° of phase shift). The dashed lines represent the height where the width of the gap is respectively 1 Body length and 2 Body lengths

5.3.5 Bridge dissolution

The bridge dissolution is also an important part of the process of building a bridge. Indeed, we want a highly adaptive structure that would adjust depending on the traffic so that the ants do not get stuck in an unused structure.

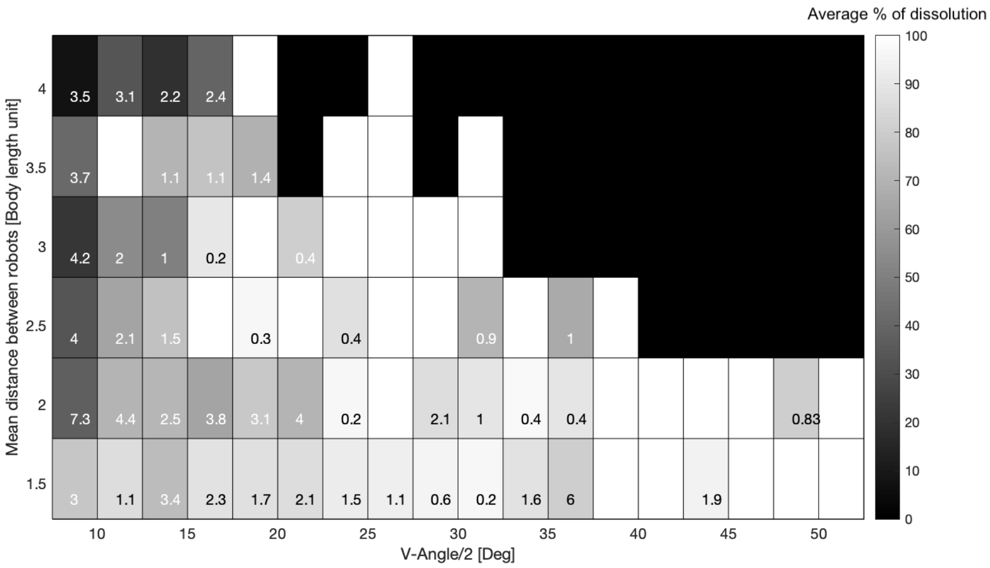


Figure 5.14: Average percentage of the dissolution over the 10 set of experiments with a gaussian delay distribution for the robots creation. Each column corresponds to a given value for the V half-angle while each row corresponds to a given value of the traffic specified as the gaussian mean distance between two successive robots. The darkest a box is, the lowest is the average percentage of dissolution. The numbers in the gray boxes are the average number of robots still stuck at the end of the dissolution step.

The dissolution is clearly not total for every pair of parameters (see Figure. 5.14). On average only a few number of robots are stuck at the end of the dissolution step (around 2). The dissolution appears to be less robust for the smallest value of the V half-angle (7.5°) and more surprisingly the lowest value of the traffic (which corresponds to the gaussian's mean distance of 3.8 Body lengths or a delay of 7.25 s). To have a better understanding of what are the causes of a partial dissolution, we looked individually at 73 failed dissolution and the possible causes were the same than the one observed with a constant delay distribution: up-grab, double-grab, geometric constraints or a repetitive pattern (section 3.3). The results are gathered in the following table:

Up-grab	**Double-grab**	**Geometric constraint**	**Repetitive pattern**
$\frac{25}{73} \approx 34\%$	$\frac{17}{73} \approx 24\%$	$\frac{22}{73} \approx 29\%$	$\frac{9}{73} \approx 13\%$

While the up-grab situation is the predominant one, it has to be weighted against the fact that a non-negligible proportion of the up-grab are due to geometric constraints. Indeed, some of them are created after a robot in the walking state goes through the not flat surface of the bridge and get stuck in the current bridge structure, having no other choice than creating a joint. We still categorized these failures as up-grab as a possible solution to resolve the issue (which will be discussed in a next chapter) could be the same than the one used for expected/usual up-grab.

In addition, all of the repetitive pattern situations and another part of the up-grabs are due to some robots from below the structure wanting to leave before the one from above as they are not walked on anymore. Any of this situation is a consequence of the 2D world as these robots have no escape from the side of the bridge whereas real ants often escape from the side.

Another observation is that, on the 73 failed dissolution analyzed, 53% of the observed double-grabs were obtained for the lowest value of the traffic (a gaussian's mean distance of 3.8 Body lengths). This could explain the previous results and the observation that the lowest traffic value led to the less robust dissolution. In addition, this phenomena might be due to additional constraint and time sensitivity on the gripper creation introduced by the 90° limit on the ran angle to avoid pushing. Thus, to have two robots creating a grip at the same time, it has to be perfectly timed out and the space between the robots should be comprised within a really specific and small interval.

5.4 Varying the terrains, the 2 Body lengths hypothesis

5.4.1 Truncated V shape

In the previous section, it has been observed that the bridge formation seems to follow a trend of forming where the width of the gap is 2 Body lengths. To verify that this width is somehow of particular importance, we ran a new set of experiments on a new kind of terrain. This terrain is the same V, so that we can vary the angle the same way we did previously, but with the apex cut to obtain a width of 2 Body lengths at the bottom (Figure 5.15).

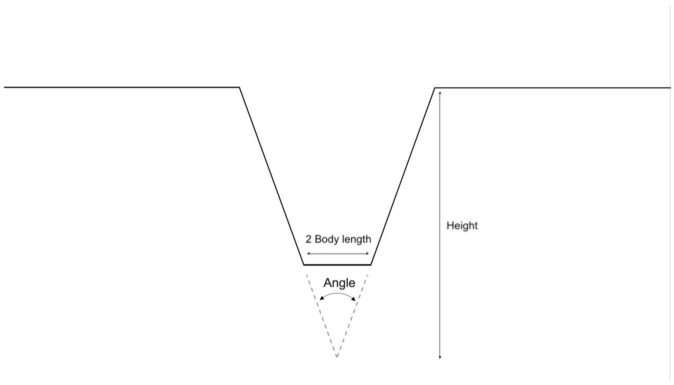


Figure 5.15: Schema of the truncated terrain used to test the importance of the 2 Body lengths width. The height of the V and the angle corresponds to the one of the initial V (before being cut).

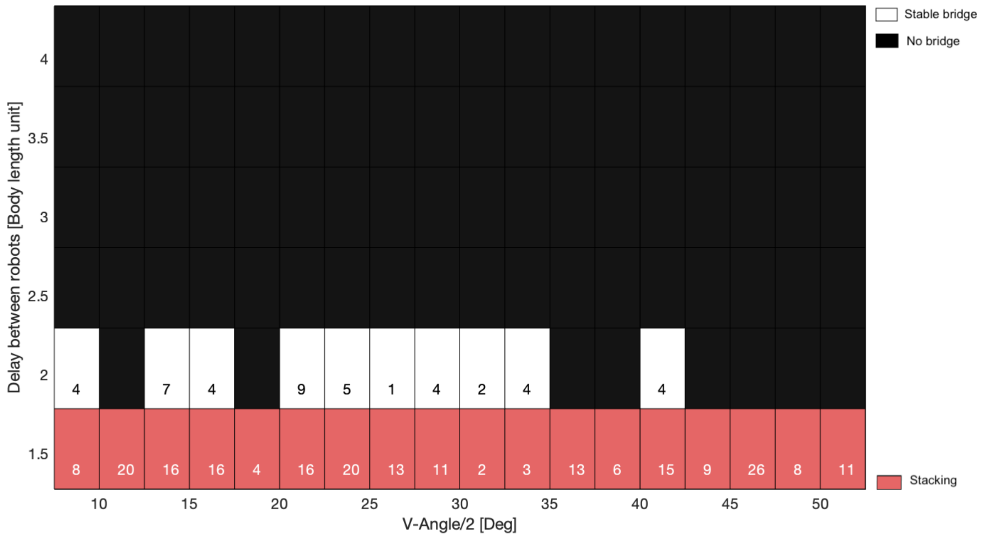


Figure 5.16: Stability of the final bridge depending on the traffic expressed as the distance between robots (vertical axis) and the half-angle of the V (horizontal axis). The numbers on the meshgrid represent the number of robots involved in the bridge.

The results tend to confirm the previous hypothesis (Figure 5.16). They show that no bridges are formed for a lower value of the traffic. If the traffic is too high we are still observing the piling-up of the robots. The only situation that led to a stable bridge without stacking is for the same value of relatively high traffic where we were previously observing bridges over the 2 Body lengths trend. However, we were previously observing 100% of the experiments with this traffic value and an half angle above (40°) leading to a bridge formation. Even if a single set of experiments has been run with this terrain, the proportion of bridges seems to also be reduced for this traffic value.

5.4.2 Ramps

When the experiments are done with a ramp terrain the overall results are similar to the previous ones. Because the Ramp is similar to a V-shaped gap with a 45° half angle but different entrance angles, no bridges are formed for a low to medium value of the traffic. The stacking is still observed every-time for a too dense traffic and the "higher traffic situation" previously described leads to a stochastic bridge formation. Thus, the results will not be discussed further.

5.5 Varying the rules

Having now a better understanding of the bridge formation and dissolution, it becomes possible to vary the rules and study their impact. To do so while limiting the number of required experiments, we went back to the fixed delay traffic for each experiments.

5.5.1 Pushing angle

In the modelling chapter (section 3.3), we presented how we made the model more specific by adding a minimum angle the robot have to run to avoid pushing, i.e. to create a gripper directly. This angle has been set to 90° to match the neutral position of the real robot. However, the previous results highlighted that often the bridge only form to suppress the contact, i.e. around the height that corresponds to a 2 Body lengths width. This is because there is no incentive to reduce the overall path length. A way to act on this could be to add a penalty when crossing the terrain obstacle. Increasing the limit angle require before pushing can be seen as a way to increase the penalty for the robots walking over any non-flat terrain (with a sharper angle than 180°).

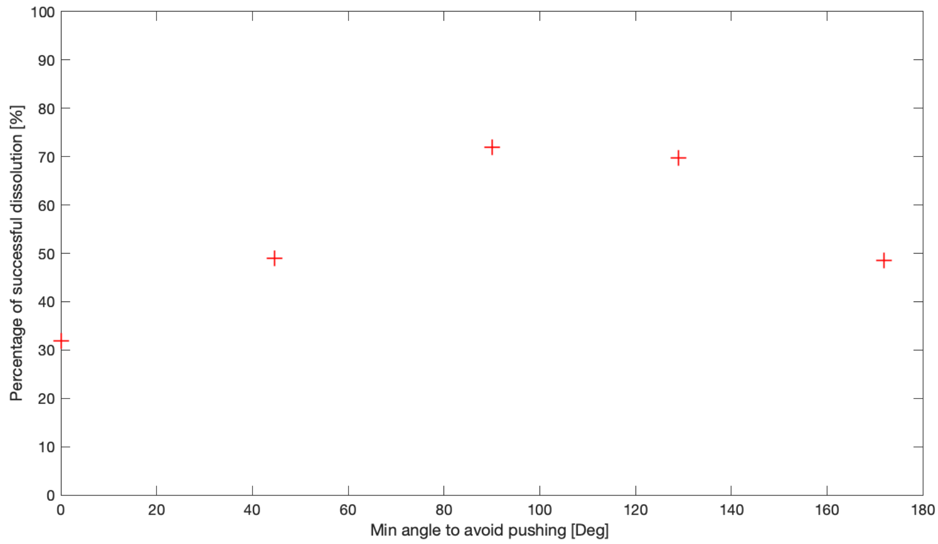


Figure 5.17: Percentage of total dissolution observed for different value of the minimum angle required to avoid pushing. For every limit angle, a single set of experiments over the all range of parameters is done. Regarding the range of parameters, the half angle varies from 7.5 to 50° with a 2.5° step and the traffic from 2.25 to 7.25s with a 1s step (i.e. from ≈ 1.3 Body lengths to ≈ 3.8 Body lengths)which lead to a total of 108 experiments per set. The delay is controlled with a constant distribution and thus the phase shift is fixed to 90°.

The current choice of 90°, for the minimum angle required to avoid pushing, corresponds to the highest rate of total dissolution with 71.9% of dissolution compared to the only 31.9% with a limit angle of 0° or the 48.5% with a limit angle of 171°. This angle also influence the causes responsible for the dissolution failures. In fact, when decreasing this angle to 0°, the proportion of double-grab increases to reach 63% of the total failure causes and becomes the main cause of failure. The increase of the double-grab can be explained by noticing that, by reducing the minimum angle required to avoid pushing, it is easier for the robot to create a gripper. The more the angle is reduced, the less the gripping condition is restrictive leading then to an overall higher number of gripper created.

On the contrary, when we increase this angle to almost 180°, the number of up-grab is increased to 60% of the causes of failed dissolution. In fact, the robots that go over the bottom of the V become in advance in their motion cycle compared to the one still on the first slope of the V. Thus, when the one on the second slope (right side) contact the robots on the first slope (left side), they have started to decrease their pushing delay sooner, thus being able to create a gripper before the one entering the bottom. The proportion of failure causes are summarized in the following table:

Pushing angle	Up-grab	Double-grab	Geometric constraint	Repetitive pattern
0°	$\frac{7}{32} \approx 22\%$	$\frac{20}{32} \approx 63\%$	$\frac{13}{32} \approx 41\%$	-
90°	$\frac{5}{16} \approx 31\%$	$\frac{3}{16} \approx 19\%$	$\frac{7}{16} \approx 44\%$	$\frac{1}{16} \approx 6\%$
172°	$\frac{21}{35} \approx 60\%$	-	$\frac{14}{35} \approx 40\%$	-

5.5.2 Entering bridge condition

Double contact

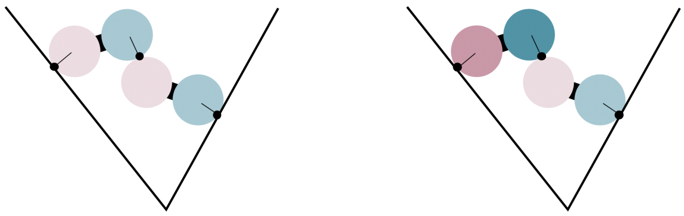


Figure 5.18: Comparison between the new rule and the previous one. A paler color indicates that the robot is in the bridge state.

As laid out in the Implementation chapter (section 3.5), the collision between two robots is possible with both robots responsible for the contact (it means both touching with their moving wheel while moving, that were called "contactors" in section 3.5). Currently, when this situation happens both robots will enter the bridge state even if only the one that went through the limit angle (of 90°) create a gripper (Figure 5.18). When both robots went through this angle, it leads to double grab. Nonetheless, when the condition is slightly changed: instead of both robots entering the bridge state the one that create the gripper stays in the walking state, the results are already really different. Indeed, it leads to the emergence of a new kind of behavior compared to the previous fixed delay experiments: for a given traffic the V-shape is filled totally with robots without having them piling up at the entry of the obstacle. Nevertheless, the total dissolution appears to be less robust going from the previous 82% observed with a constant delay distribution to only 33% of total dissolution.

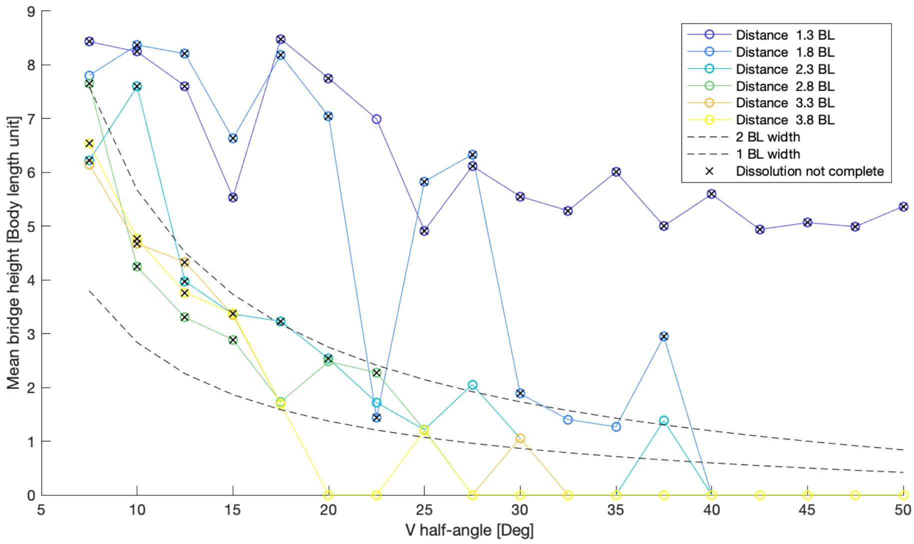
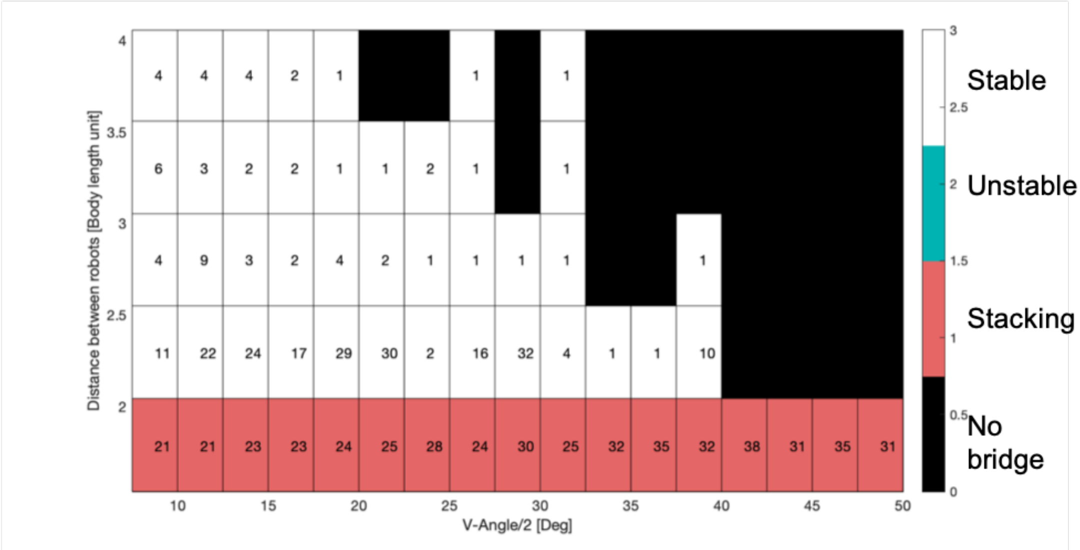
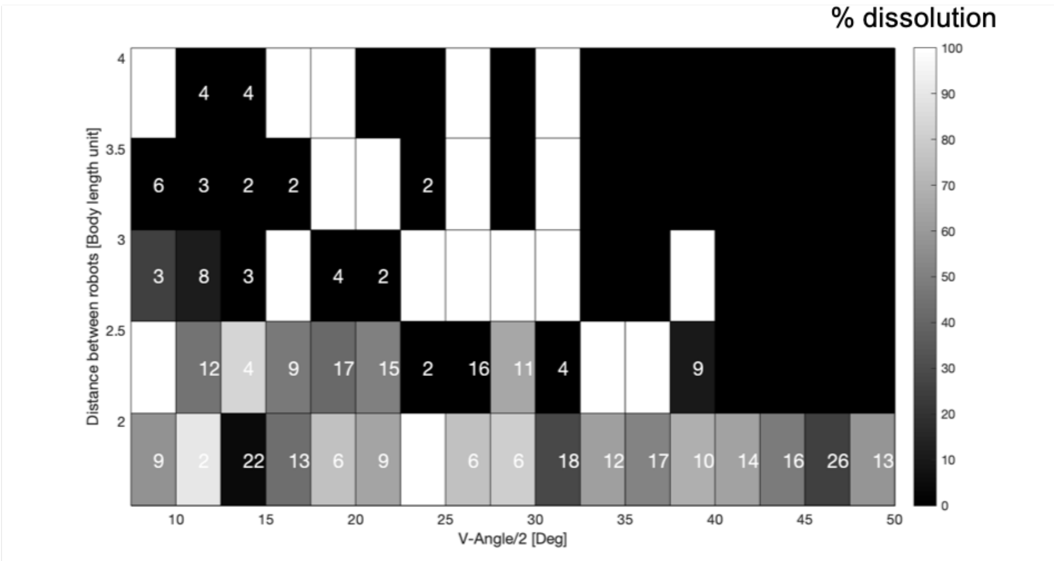


Figure 5.19: Evolution of the bridge mean height as a function of the V-half angle when the traffic is fixed (with a phase shift of π i.e. $180°$) . The dash-lines represent the height which correspond to a width of the V-shape of 2 Body lengths units and 1 Body length unit.



(a) Stability of the final bridge depending on the traffic expressed as the distance between robots (vertical axis) and the half-angle of the V (horizontal axis). The numbers on the meshgrid represent the number of robots involved in the bridge.



(b) Percentage of dissolution at the end of the simulation depending on the traffic expressed as the distance between robots (vertical axis) and the half-angle of the V (horizontal axis). The darker is the bin, the less the bridge has dissolved. The numbers represent the number of robots stuck in the bridges at the end of the simulation.

Figure 5.20: Bridge stabilization and dissolution results for a set of experiments controlled via the delay with a phase shift of π and the movement blocked in bridge state, but with a second version of the bridge entering condition.

When the dissolution results are analyzed individually, it appears that the issues are due to an increase in the geometric constraints. Indeed, because the bridge is constructed by one robot at the time, the basis of the structure is less rigid (because no link between the two sides of the V are formed as leading to the slipping of the robots at the bottom of the structure due to the frequent stepping over. This slipping leads to the geometric constraints by impacting the robot trajectory. This phenomena is amplified by the relative freedom of movement ($\pm 30°$) in bridge state. Indeed, the confirmation has been obtained when removing this freedom and going back to the previous design choice where the robots were totally blocked in bridge state. If the bridges still form at the same place most of the time they involve less robots and the dissolution, even if far from being as good as the previous results, is slightly improved (section A.3).

Chapter 6 Discussion and conclusion

6.1 Overview of the results

From the experiments, it appears that there are four types of behavior summarizing the bridge formation:

- Too high traffic: stacking situation, the robots are piling up at the entrance of the bridge without actually forming a bridge.
- High traffic: a bridge is formed, generally higher than the height corresponding to 2 Body lengths width.
- Low traffic: a bridge is formed, following a 2 Body lengths trend, generally involving a few amount of robots.
- Too low traffic: no bridge is formed.

Two of this situations are especially interesting: the low and high traffic. Regarding the low traffic, it appears that the bridge is generally not formed above the height corresponding to a 2 Body lengths width. In fact, the bridge act as a collision suppressor but the robots have no real incentive to join the structure. Indeed, they are not motivated by an explicit efficiency requirement regarding the path optimization. In addition, the collision are totally suppressed when the bridge reached this 2 Body lengths width, and it has been confirmed by using truncated terrains. This is partially due to the fact that, even if small perturbations are added to the traffic thanks to the Gaussian distribution of the delay, the speed and the resting delay are the same for all the robots, thus limiting the probability of unpredicted contacts. In addition, the model is perfectly rigid, meaning that, unlike the real robot, its body does not extend during its movement thus reducing the actual area of possible contact.

The second interesting case is the exception of the really high traffic which is at the edge between the stacking situation and the low traffic one. Indeed, this case was never observed with a fixed value of the delay, but appeared when adding some perturbation into the system by controlling the delay via a Gaussian distribution. By doing so, we introduce both robots matching the low traffic criteria and others doomed to stack (because too close from one to another). This last type of robot is injected into the system in a discontinued way letting the time for the structure to recover. The final height of the bridge will depends on the proportion of robots doomed to pile up injected into the system but also on the duration of the experiment in our case (which could correspond to the duration of the raid when doing the parallel with real ants) or more generally the duration of a high density wave/period and the recovery time between successive waves.

6.2 The bridge: a traffic regulator

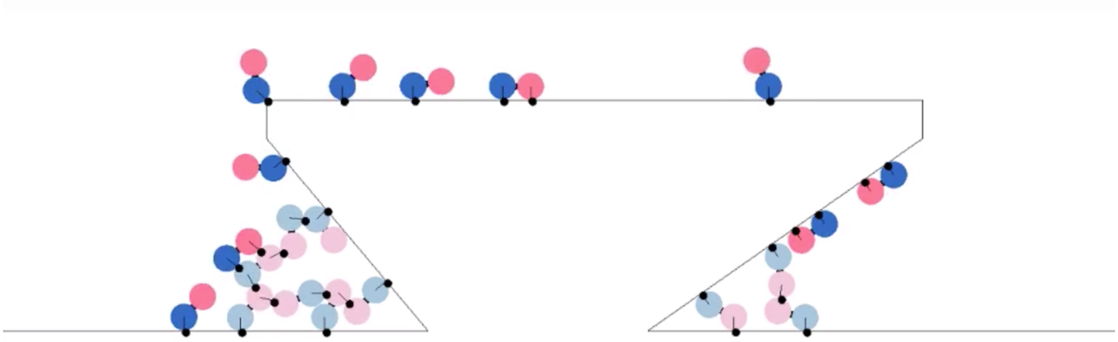


Figure 6.1: Bridge formation on a complex terrain. 25 robots are created with a Gaussian distribution of the delay centered on a high traffic value (delay of 3.25s i.e. a distance of 1.7 Body lengths). The second V-shaped gap is sharper than the first one, though the first bridge migrates further away from its bottom than the second one.

The latest test, essentially qualitative, has been run on a more complex terrain including several angles, changes in ground orientation and two V-gaps (see Figure 6.1). It introduces a set of really interesting behaviors. We created 25 robots following the Gaussian distribution of the delay with the highest traffic value excluding the stacking situation (mean of the Gaussian of 3.25s i.e. a distance of 1.7 Body lengths and a phase shift of 90°, with a standard deviation of 0.25s i.e. of 90° in phase shift).

The angle of the second V-shaped gap is sharper than the one of the first V-gap and should thus lead to a higher bridge respectively to the bottom of the V. But It appears that the bridge formed in the first V-gap migrates further away from its bottom than the one in the second gap. In fact, this first V-gap acts as a buffer that regulates the traffic of the robots. Nonetheless, such a phenomena would have most probably not been observed if we had injected more robots into the system. Indeed, we believe that each V-gap has a certain capacity of "absorbency" and when this capacity is full, it will keep filling the next gap until the traffic stops or is finally regulated. A way to characterize and quantify this phenomenon more precisely, in future work, could be to create terrains with a succession of similar V-shaped gap. One could then be able to play with the size/duration of the robot burst, the angles of the successive V and the waiting delay in the bridge state.

Another interesting phenomena is that some of the robots have time to leave the bridge in the second V-gap before the traffic actually stops. Indeed, as robots were entering the bridge state in the first gap, it created a discontinuity in the traffic at the output of this gap. It leads to the observation of a dynamically stable bridge in the second gap. It is a promising result for further test with the adaptation or variation of the delay in bridge.

6.3 Perspectives

There are two major axes for the future development of the project: either by concentrating on the specific case of the high traffic or by focusing on the low traffic cases.

6.3.1 Low traffic focus

As explained previously, currently, the robots have no real incentive to join the bridge so the height is usually limited. It is sufficient if the goal is only to suppress the collision but not if the final objective is to optimize the path length. In this case there should be an incentive for the robots to join the bridge but also a cost to counter-balance the growth of the bridge and reach a trade-off. It could be interesting to implement a market based approach inspired by the articles discussed in section 2.1. The benefit could be the actual reduction in the path length and the cost could be the number of robots involved in the bridge. This last parameter should be adjusted to take into consideration that, because we are working in 2D, no robots can escape from below the bridge. To implement this approach, the implementation of the simulator could be adjusted so that the robots join the bridge with a certain probability when stepping over it. This probability could be function or not of the current width, or height, or number of robots involved in the bridge. This would help the structure to grow from the initial contact nucleus but will not influence at all the situation where no bridges were initiated from a first contact.

6.3.2 High traffic focus

The other axe of research could be to focus on the specific case of high traffic and especially play with the proportion of robots doomed to stack introduced in the system. It would be a way to increase the height of the bridge above the 2 body-length width without explicitly adding a benefit for the swarm when the robots join the structure. It will take advantage of the property of the bridge to regulate the traffic by "absorbing" the robots that are doomed to collide. A way to do so could be to play with the traffic shape of the robots. One could implement a periodic delay resembling the one presented in section 2.1.

But a more controllable way to do so considering the discreet aspect of the time domain could be to inject burst of high density traffic, either following a periodic square distribution oscillating between high density traffic and no traffic or a more irregular one oscillating between these two same states.

It will most probably require to adjust and play with the delay in the bridge in order to reach an equilibrium between the robots entering the bridge and the one leaving it. One could, for example, consider adding stochasticity in the delay in bridge determination within a single run of the simulation.

6.3.3 General self-assembly perspectives

While the perspectives regarding the bridge formation are numerous, it might also be interesting to try to implement other structures. The robots could aim at building tower, chains or cantilevers. The basic rules that have been implemented for the bridge formation could still be valid to build other structures. In fact, we can interpret the current system as the robots having a goal direction which corresponds to the other side of the bridge. This is why they have a linear speed. But it might be possible to change the goal/target position, and adapting the speed to reach this goal. In order to build a tower, one may consider adding a target position above the robots and handle the speed according to a gradient.

6.4 Simulation concerns

6.4.1 Generalities

Programming the simulator was a sensible task and any minimal change to any configuration parameter such as the robot speed, dimension, the torque... can lead to significant changes in the results of a given experiment with the same initialization. Nonetheless, I believe that the overall evolution of the results should stay the same. While the critical values of the traffic or the angle separating the different situations might vary slightly, the situations should stay identical. We should still be able to observe a specific value of the traffic leading to a higher bridge, one to stacking and lowers value following the two Body lengths trend.

6.4.2 Possible improvement

Apart from the possible implementation improvements and the necessity to optimize the simulation, one could think about ways to resolve the dissolution issues. The geometric issues could be resolved by adding even more flexibility into the system. For example, the grippers could be modelled with a certain springiness instead of just being pin joints. In addition the overall body of the robot could be more deformable. If a springiness is also added to the feet attaches, it might even come closer to the real robot trajectory. To justify the addition of the flexibility, it might be required to do some physical tests with the real robot in order to determine correct values.

The up-grabs could be resolved by adding a condition allowing the robot to change its gripped foot every "delay in the bridge state" when it is still moving. This way, it would let the time to the robot above to escape from the bridge state. Adding some stochasticity in the delay or the detaching action might also be a solution but might have a higher impact on the results.

The double-grabs could be resolved by adding stochasticity too in the detaching action.

And Finally repetition might be avoided when reducing the delay in the bridge state.

Nevertheless, these dissolution failure might be avoided if the fact that 2D worlds introduce additional constraints is acknowledged. Indeed, in a 3D world, many of this situations would not happen as the robots from below the structure would be able to escape it from the sides.

6.5 Conclusion

Literature review laid out the current lack of robots swarm able to self-assemble in complex structure, solely based on environmental cues and without a central supervision. The Flippy[5] robots was built in order to replicate structure found within insect societies following minimalist local rules. This project implemented a 2D simulator for soft robots focused on Flippy that demonstrates self-assembled bridges can form and dissolve under simple rules. This work investigates the impact of environmental cues on the bridge formation and its dissolution. Experiments have been conducted with the simulator to vary the geometry of the terrain and the traffic of the robot. Bridges are formed for sufficiently high traffic value and sharp gap; and the transition between the no bridge situation seems stochastic. When the traffic is too dense the robots are stacking up at one side of the bridge (Figure 6.2). The results also highlighted some trends in the bridge shape. Finally the dissolution has been observed but was limited by the constraints of the 2D world

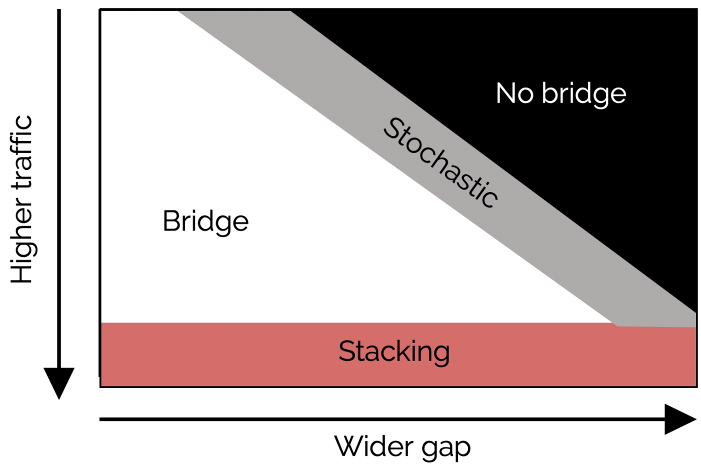


Figure 6.2: Schematic representation of the bridge formation as a function of the traffic and geometry

6.5.1 Next step for the team

However, before digging into the possible perspective with the simulator, it is necessary for the team to try to implement some basic situation with the real hardware. Indeed, the results need to be compared to what can actually be obtained with the real robots. Moreover, to improve the simulation, it is necessary to have feedback from physical experiments. Those future tests might highlight the necessity of changing some model parameters or take new design choices. The short term objective is to start by implementing 3 or 4 robots walking onto each other.

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Lucie Houel: Self-assembly of soft-robots in simulation

Signature

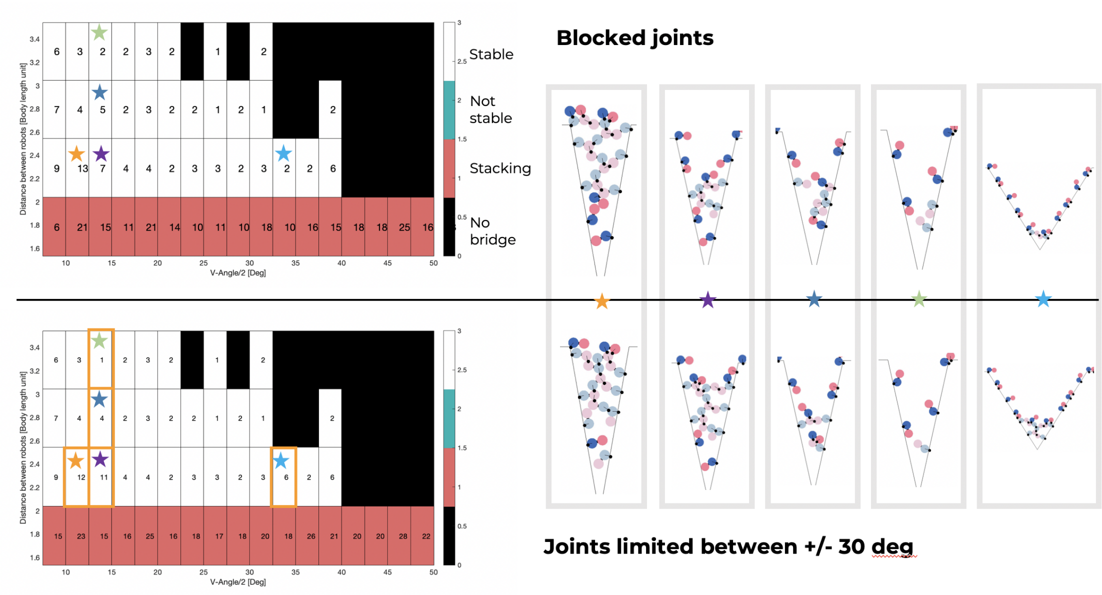
Harvard, March 15, 2019

Lucie HOUEL

Appendix A Experiments details

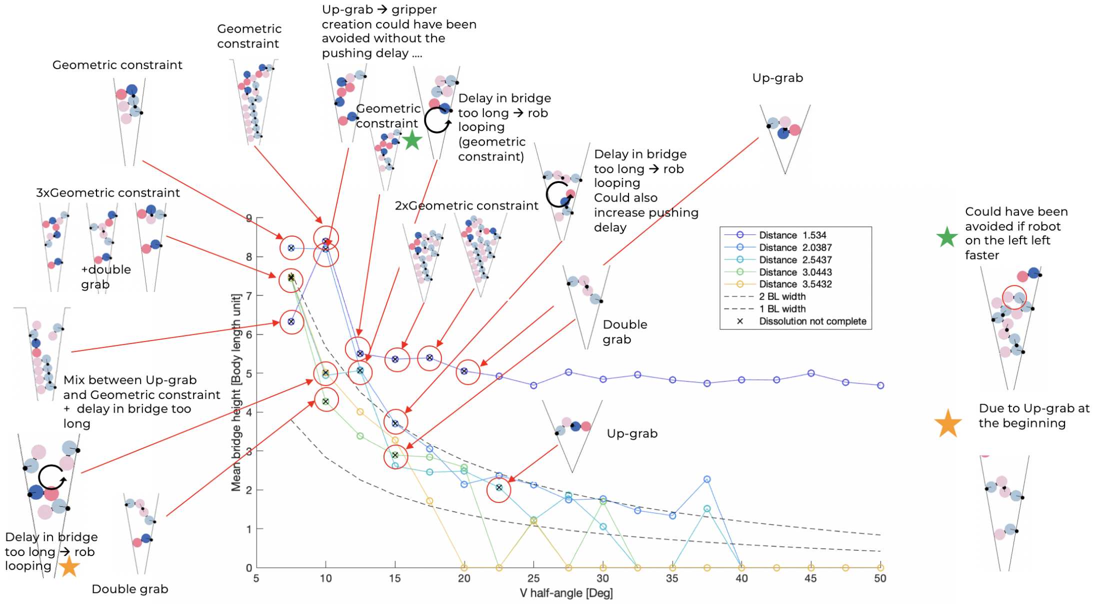
A.1 Details on the difference between the results for fixed and limited joints in bridge state

The final bridges of two set of experiments have been compared. The two sets are done with the usual setup, a fixed distribution of the delay between the robots and a fixed phase shift of π. One set is done with the joints of the feet of the robots blocked in the bridge state, the other with the rotation of these joints limited between $\pm 30°$



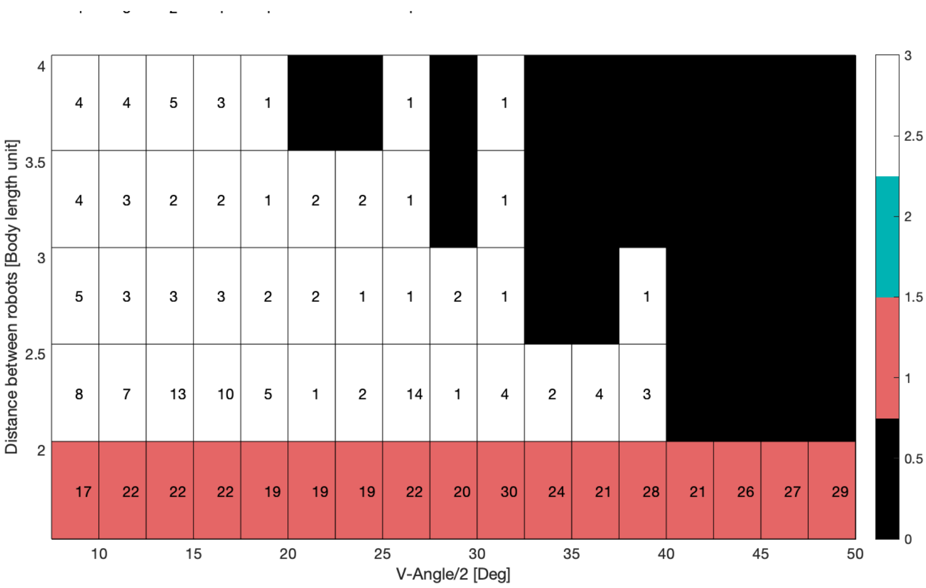
A.2 Dissolution failures

Every dissolution failure of a set of experiment have been reported. The set is done with the usual setup, a fixed distribution of the delay between the robots and a fixed phase shift of π. The dissolution failures are associated with their position in the mean height bridge curves.

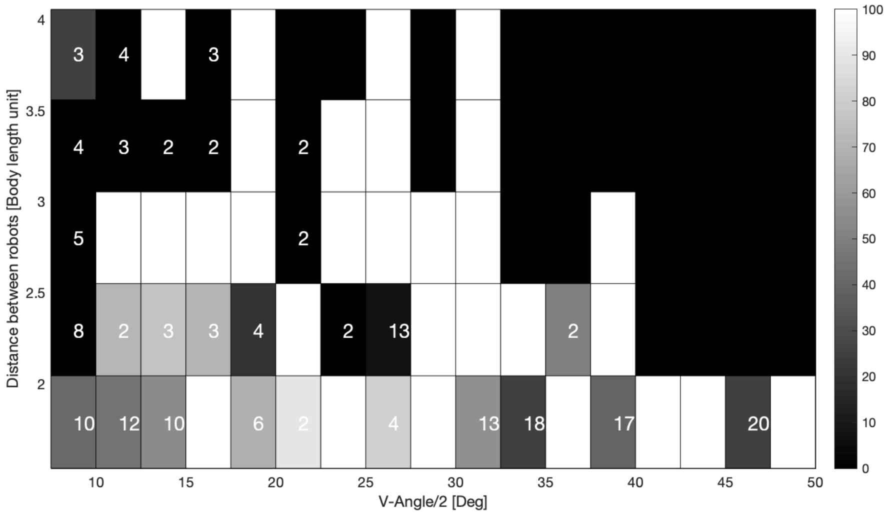


A.3 Results with the new entering bridge condition with blocked joints

Changing the entering bridge condition increased the geometric constraints due to a less stable basis of the bridge structure (section 5.5). A new set of experiment conducted with the usual setup, a fixed distribution of the delay between the robots and a fixed phase shift of $\pi/2$, showed that blocking the rotation of the robots in the bridge state slightly improved the dissolution.



(a) Stability of the final bridge depending on the traffic expressed as the distance between robots (vertical axis) and the half-angle of the V (horizontal axis). The numbers on the meshgrid represent the number of robots involved in the bridge.



(b) Percentage of dissolution at the end of the simulation depending on the traffic expressed as the distance between robots (vertical axis) and the half-angle of the V (horizontal axis). The darker is the bin, the less the bridge has dissolved. The numbers represent the number of robots stuck in the bridges at the end of the simulation.

Figure A.1: Bridge stabilization and dissolution results for a set of experiments controlled via the delay with a phase shift of π and the movement blocked in bridge state, but with a second version of the bridge entering condition.