VIII MODELLING WEEK

9th-13th June 2014

COGNITIVE MANIPULATION IN ROBOTS AND ARTIFICIAL AGENTS

Francisco Llaneza González

Javier Álvarez Liébana

Carlos Calvo Tapia

COMPLUTENSE UNIVERSITY OF MADRID

Contents

1. Introduction.

This report contains the work done during the VIII Modelling Week in Complutense University of Madrid, from 9^{th} to 13^{th} June.

With this report we want to extend all about our oral speech in the last day of Modelling Week. During that workweek, the group was formed by Javier Álvarez Liébana (UCM), Carlos Calvo Tapia (UCM), Michael Gómez (University of Oxford), Francisco Llaneza González (UCM) and Vasily Mironov (University of Nizhni Novgorod). We were supervised by José Antonio Villacorta Atienza.

This paper has been created by students mentioned above which are enrolling in the Master of Mathematics Engineering in UCM: Javier Álvarez Liébana, Carlos Calvo Tapia and Francisco Llaneza González.

2. Cognition.

Throughout this work we'll talk about cognitive manipulation, so first of all we must define the concept of **cognition**. **What does cognition mean?** If we look it up in Oxford English Dictionary (OED), we will find the next definition:

> **2.** *Philos.*
>
> **a.** The action or faculty of knowing taken in its widest sense, including sensation, perception, conception, etc., as distinguished from feeling and volition; also, more specifically, the action of cognizing an object in perception proper.

We could think that cognition is "just" learning, like an algorithm to classify patterns or make clusters. But it's much more than that.

Cognition is a set of mental abilities for the processing of perceived **<u>information permitting decision making for interacting with the environment</u>**.

As we'll see, this definition can be divided in three main parts:

1. Set of mental abilites for the processing of perceived information
2. …permitting decision making…
3. …for interacting with the environment

It's **<u>important to underline each one</u>**, as we'll see later.

If we wanted to build some system or robot that was able to mimic brain's cognition, we would have to understand how our brain works. It's known that the brain is designed to understand little pieces of information. How? Through cognitive maps.

3. Cognitive maps.

Let's see an example of cognitive map.

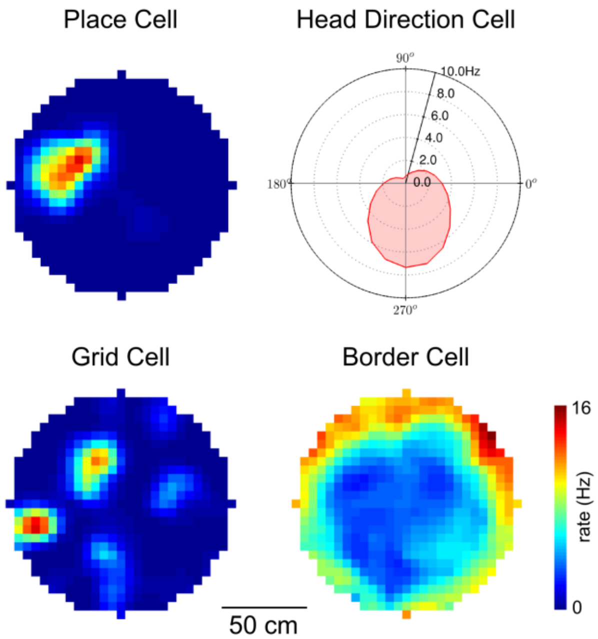


Figure 1: *Some results about experiment with the rat's brain, retrieved from Davidson TJ, Kloosterman F., Wilson M.A. (2009), Neuron 63(4): 497—507.*

The picture above shows us some of the results of a research with brains of rats which were situated in a cylinder. Every neuron in the rat's brain represents a concrete location of the space.

The neuron or cell denominated **"Place Cell"** is responsible for codifying and "encrypt" our spatial situation in relation to the external environment. The showed neuron will be activated when we are in the red area (with more activation) of the cylinder. If we were in another place, this neuron specifically would be completely blue (without activity), being the neuron in charge of the new location the one that would be activated.

The neuron named **"Head Direction Cell"** codifies and abstracts the information about the orientation off the head of the rat: in which angle looks at the rat in relation to its environment.

The one called **"Grid Cell"** provides to us information of the metrics of the space: the represented neuron is activated in the way we can see in the image because it is in charge of codifying the metrics of the above mentioned regions of the cylinder.

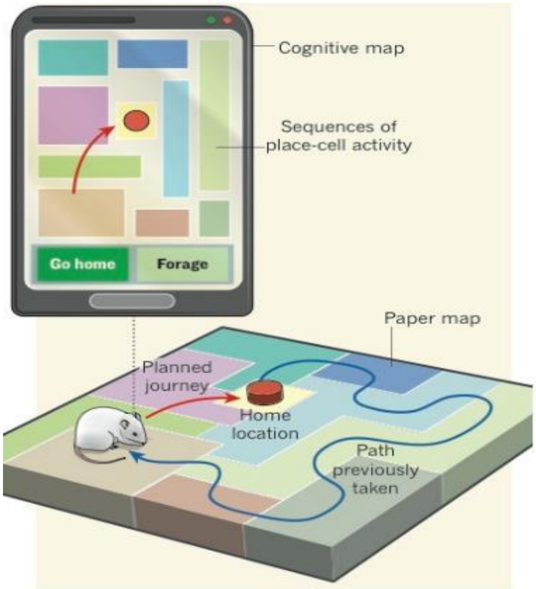


Figure 2*: Cognitive map in the rat's brain*

And finally the neuron called **"Border Cell"** provides us with the limits of the cylinder.

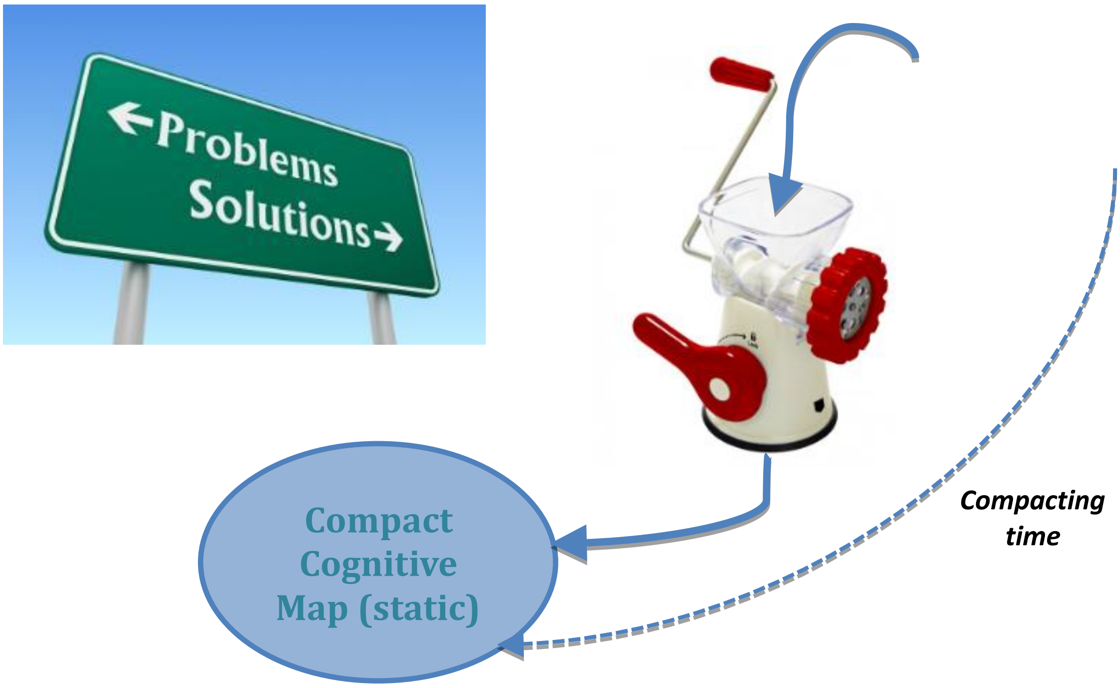
All this information provides the brain of the rat species with a map of the space that surrounds it. This way, the brain obtains an abstract representation of the static space that surrounds the rat and the set of possible routes that the animal can choose to reach its target. All this compressed and codified information forms the cognitive map associated with the above-mentioned static situation.

4. Compact Cognitive Maps (CCM).

We have already seen how the brain is capable of codifying static information in a kind of map. The **difference between this cognitive map and an urban map** that we can obtain when we do tourism is that the cognitive map does not only codify the locations and metrics of the environment but it provides the brain with a wide range of possible movements depending on each situation.

But fortunately the **nature is dynamic, not static**. Almost all the situations our brain must face are dynamic: driving, walking, practicing sport, etc. So, there are a huge number of simple but dynamic situations that we do not know how our brain is capable of codifying them.

How can we solve and make a model of this problem? Thanks to a compact cognitive map. With him we try to codify and transform a dynamic situation, through compacting in time, to obtain a static representation of the dynamic situation.



In the following sections we will see how to **simulate this cognitive compact map (CCM)** and how it is possible to apply it not only to navigation but also to problems of manipulation. The mathematical base that we will use for the modelling are the neuronal networks of Fitz-Hugh Nagumo (a change of the same ones).

5. Navigation in dynamic situation.

Two elements are required when we want to navigate in a dynamic situation, chasing a target by avoiding collisions against obstacles. **Prediction** and **Mental Simulation**: both of them are mental processes in human brain. Prediction is the estimation of the future behaviour of something. And for Mental Simulation we consider all the possible movements that we can carry out.

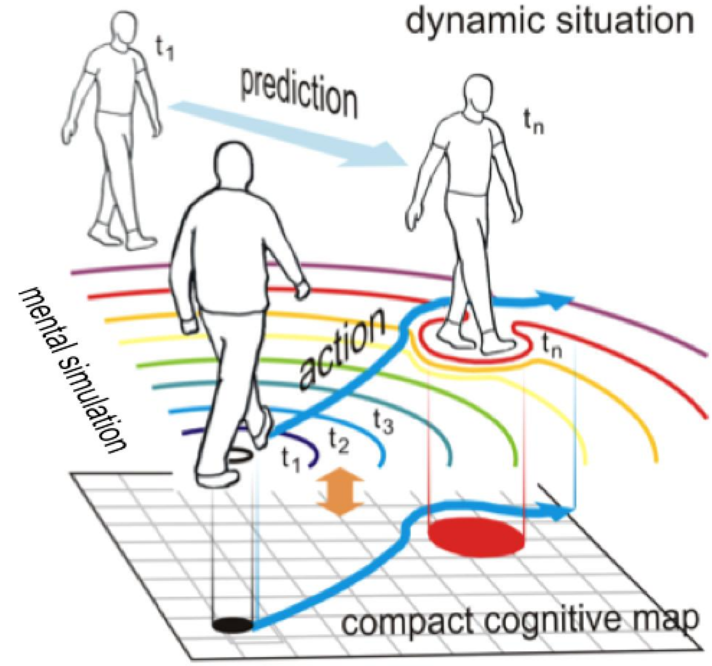


Figure 3: *Interaction of prediction and mental simulation. The cognitive subject (dark black line) predicts the movement of a pedestrian (light black line) and simultaneously simulates its own possible actions (coloured curves denote possible agent's positions at different times). Coincidences of its possible actions with the predicted pedestrian's movements form a static effective obstacle (red area) leading to the compact cognitive map. Avoidance of this static obstacle following routes contained in the map ensures collision-free walking.*

The solution we propose to solve the paradigm of navigation is an approach based in a **reaction-diffusion model**:

- Predicted position of dynamic obstacles and targets are trivially obtained from standard equations, e.g. Newton laws. Only considering initial conditions, we can easily predict where obstacles and targets are going to be located in a short future interval of time.

- For mental simulation, we use a nonlinear reaction-diffusion system exhibiting an auto-wave behaviour, assuming for simplicity a constant velocity of the agent.

The key point is the interaction between prediction and mental simulation. It generates the special red zone in Figure 1, which represents where possible collisions could be exist. The regions of interactions are named **effective obstacles** and they are projected into a static representation of the dynamic situation: **Compact Cognitive Map**.

Now the following picture (figure 4) shows the idea behind Compact Cognitive Maps. We are going to implement a simple situation in which an agent wants to reach a target by avoiding a large moving obstacle. This obstacle moves perpendicular to the straight line that initially joins the agent with its destination.

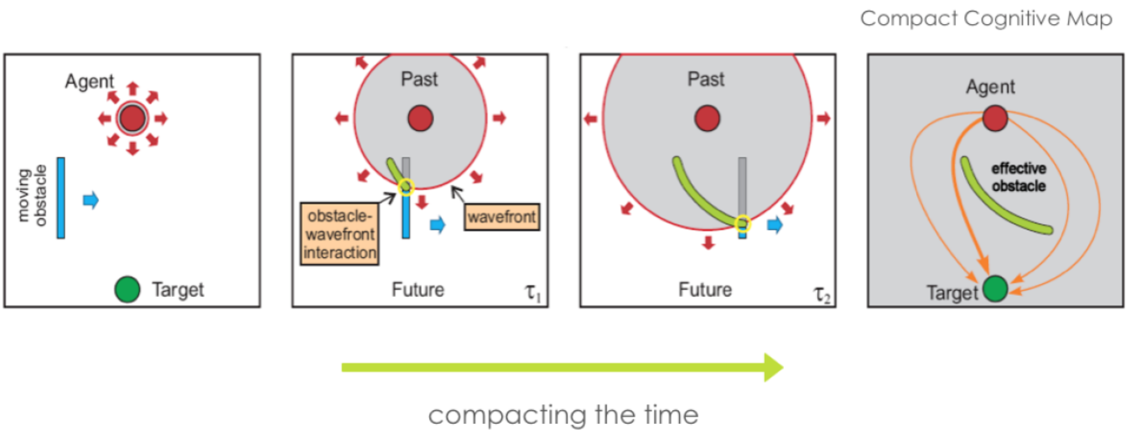


***Figure 4**: The idea behind Compact Cognitive Maps. The red circumference represents the possible positions of the agent in time. If any point of the obstacle intersects with this circumference, it means that a collision is occurring on this trajectory.*

The effective obstacle is built in time and as long as this process continuous, the final Compact Cognitive Map is generated.

These other panels (figure 5) are a numerical simulation of the previous idea. They show a propagating wavefront representing the possible positions of the agent at each moment. Finally we obtain the Compact Cognitive Map, as a static representation of the dynamic situation.

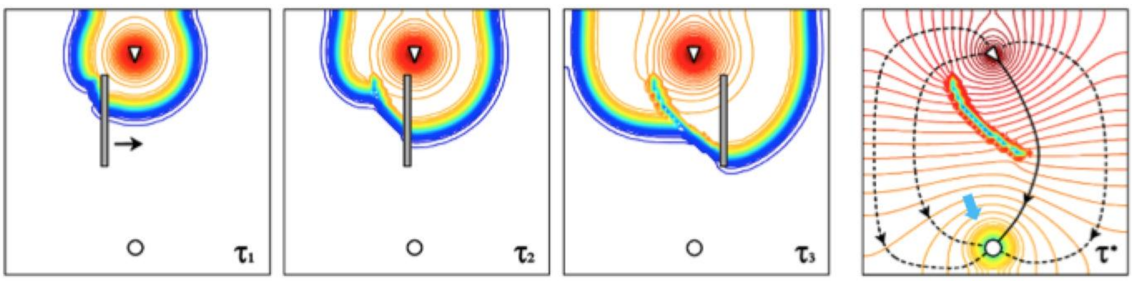


Figure 5: Numerical simulation of the dynamic situation explained in figure 4.

The wavefront's propagation generates a mental region corresponding to the spacial-time points where a collision could exist. The localization of these effective obstacles provides the agent with a global comprehension of the dynamic situation, so now it can choose how to act in consequence.

Mathematics behind this model respond to the following system of equations:

$$\dot{r}_{ij} = q_{ij}\{H(r_{ij})(f(r_{ij}) - v_{ij}) + d\Delta r_{ij} - r_{ij}p_{ij}\}$$

$$\dot{v}_{ij} = (r_{ij} - 7v_{ij} - 2)/25$$

with $d = 0.2$ and $f(r) = (-r^3 + 4r^2 - 2r - 2)/7$.

The main part of these equations is known as **FitzHugh-Nagumo reaction-diffusion system** (with two stable points in $r = 0$ and $r = 3$ and one unstable point in $r = 1$), responsible for the active propagation, which creates the effective obstacles and targets. Auto-wave generated by this way propagates conserving its shape and velocity. Mathematically, for this propagation we have considered the Ω-set:

$$\Omega(\tau) = \{(i,j): \exists \tau_0 \in [0,\tau] \mid obstacle\ in\ cell\ (i,j)\ at\ \tau = \tau_0\ and\ 0.5 \leq r_{ij}(\tau_0) \leq 2\},$$

which is introduced in the equations by means of

$$q_{ij} \equiv q_{ij}(\tau) = \begin{cases} 0 & if\ (i,j) \in \Omega(\tau) \\ 1 & if\ (i,j) \notin \Omega(\tau) \end{cases}$$

q_{ij} terms describe effective obstacles: its value is equal to zero in those cells that are simultaneously in the wavefront and in the predicted obstacle.

In the inner part of the wave front takes place the passive diffusion, responsible for the gradient profile and the creation of trajectories, once time the active propagation has covered all the space. The separation in time between passive and active diffusion is due to the H function, defined as

$$H(r) = \begin{cases} 1 & if\ r \leq 3 \\ 0 & otherwise \end{cases}$$

Finally, p_{ij} represent the target, by introducing a sink in the passive diffusion:

$$p_{ij} = \begin{cases} 1 & if\ (i,j) \in T \\ 0 & if\ (i,j) \notin T \end{cases}$$

6. CCM and cognition.

When we talk about CCM, one natural question is: **<u>why we describe these maps as 'cognitives'?</u>**, i.e how does CCM fit into the definition of cognition?. If we remember, cognition is defined as a set of mental abilities for the processing of perceived information permitting decision making for interacting with the environment. We can see that there are three underlying concepts in this definition. We are going to analyze each of them and to relate them to our context. To do this, we will use an example. Suppose we have the situation represented in figure 6:

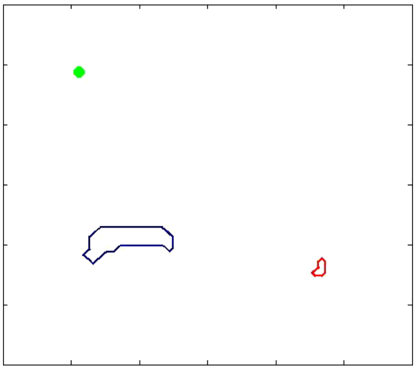


Figure 6: *Initial situation. In green, the agent; in red, the moving target; in blue, a moving obstacle*

<u>Processing of perceived information</u>

First of all, we have some initial conditions in our system. With them, we can get a prediction about the future of the situation. If in the example the obstacle and the target are moving in a straight trajectory, we can think that in a near future they will do the same. So the prediction consists on thinking future movement of the objects using the information we have seen. Then, with mental simulation we can let the system go by to obtain one final state. Those ideas are implemented by the CCM. In our example, it is represented in figure 7.

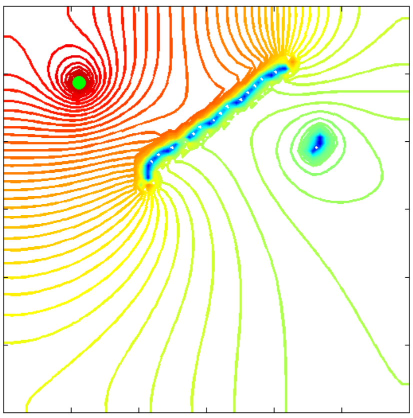


Figure 7: *Simulated CCM of the situation observed in Figure 4*

In this image we can see how the effective obstacle has been created, and also the effective target. It summarizes all information about the system and it implies the total understanding of the situation.

Permitting decision-making:

CCM give us a lot of trajectories going from the agent to the target avoiding the obstacle. So in the example, we have something like figure 8.

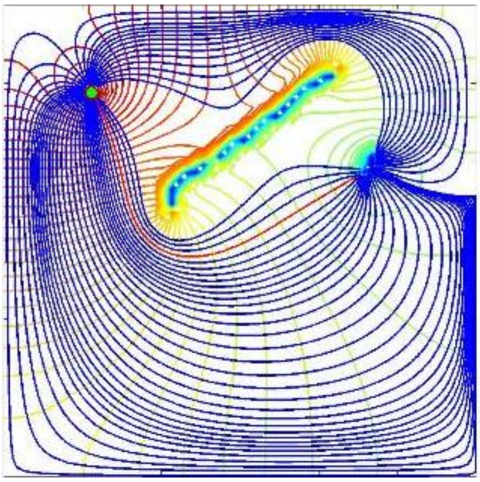


Figure 8: *Blue lines represent some trajectories.*

Lots of possible routes mean many options, and this is why CCM allow us to take decisions about our near future. The final path we choose only depends on our criteria. We can select the safest/shortest/more comfortable/… path. It's on our own. For example, the red path is the shortest and also is one of the safest because it's going behind the moving obstacle.

Interacting with the environment

Once we have chosen our final path, we can carry out an action in the real world going through this particular route. In the following images (figure 9) we can see the agent using the previous red path.

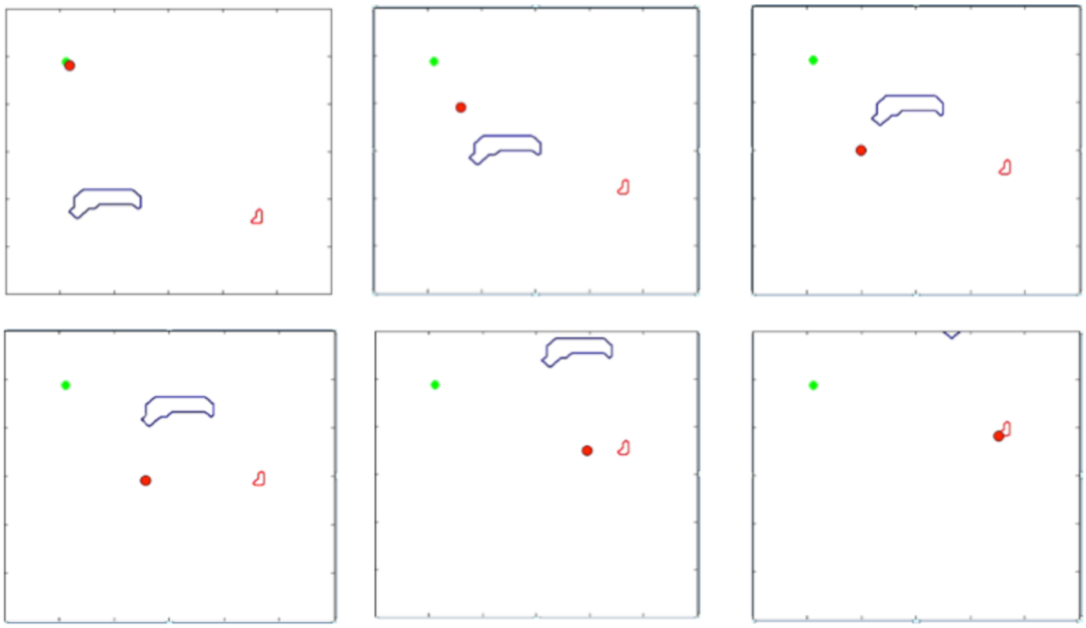


Figure 9: *Six frames taken from the video that simulates the solution.*

After these analyses, conclusions are clear: in fact, CCMs have the concept of cognition inside it.

7. Applying navigation to manipulation by CCMs.

In this section we are going to apply navigation to manipulation. In our context, **manipulation means catching targets that can be static or on the move**. There can be also static or dynamic obstacles between the agent and the target. For example, we can think in a robotic arm trying to catch a falling ball avoiding a beach disc. As we see, the extension of the concept of navigation to manipulation seems quite natural. However, there are some inherent problems we will explain below.

We consider the following situation:

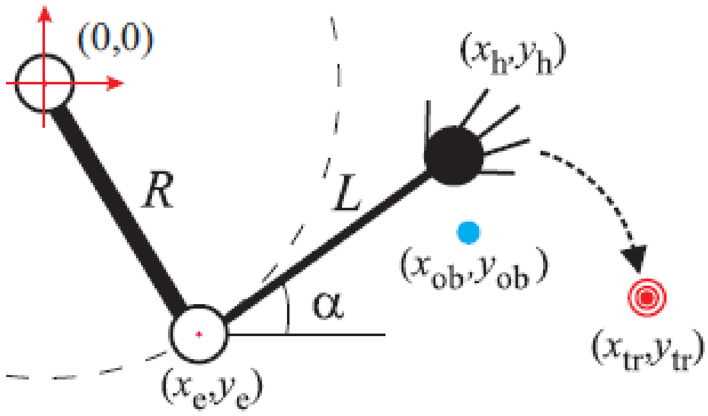


***Figure 10**: Manipulation problem's representation.*

The blue point is the obstacle and the red circle is the target. As the reader can see, this is a two-dimensional case. Also, we consider a static obstacle and a static target. We use these assumptions to understand easily how to turn a manipulation problem into a navigation problem. We will see later more complex situations but the key is to understand this example.

In navigation the agent was a single point, but in this case, which is the agent? We can represent the hand as a point to apply then the solution method we have seen in navigation, but we can't do it directly. First of all, we have to describe the hand motion depending on the movement of the shoulder and elbow joints: this is an inverse kinematic problem and we can solve it easily. The main problem is that we have to change something when we go from our real manipulation problem, represented in the *arm space*, to the associated navigation problem, represented in the *hand space*. We need to create an extended obstacle in *hand space*. If we don't do this, we could obtain solutions in *hand space* that were not feasible in *arm space* because the arm hits the real obstacle. So, **how can we construct the extended obstacle to avoid this problem?**

When we were speaking about navigation, our effective obstacle was the set of points (compacting in time) that our agent couldn't visit not to collide in this spatial and temporary point with the obstacle. Since we have already said, our agent now will be a point that represents the hand (its center of gravity), which is provided with two freedom grades: it can be articulated by the shoulder and/or by the elbow.

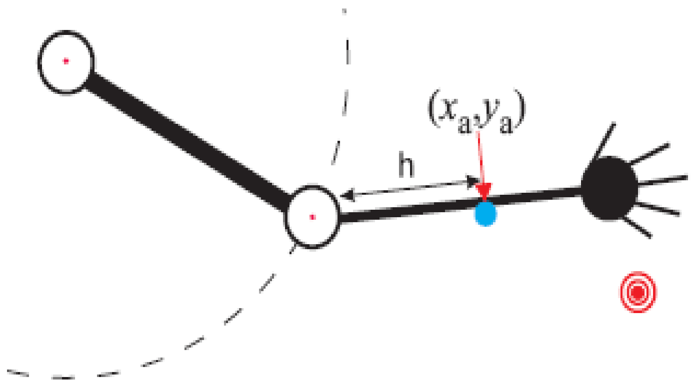


***Figure 11**: Arm colliding with the obstacle (blue point) when trying to reach the target (red point).*

If the hand tries to reach the target as in the figure, the arm will collide with the blue obstacle and we will mark with orange the position of the hand when this arm hits the blue obstacle. If we move the arm in all the possible positions in which it collides with the blue obstacle in any of the parts of the same one, and we mark all these orange points, we can obtain a "trajectory" or series of orange points that represent all the positions that the hand has when the arm hits the blue obstacle in each on its parts.

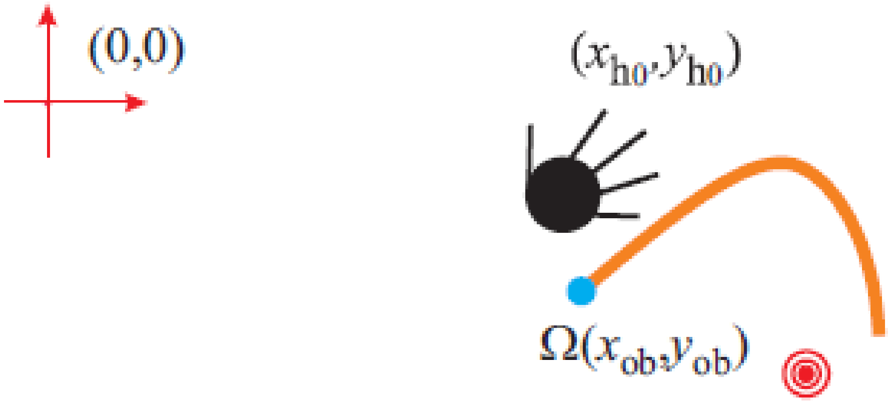


***Figure 12**: Extended obstacle (orange line) of obstacle (blue point) in the arm space*

<u>**These orange points is what we know as extended obstacle**</u>.

If we set the origin of our Cartesian coordinate system in shoulder and for the sake of simplicity, we suppose $L = 1$, the coordinates of the hand position when the arm hits the obstacle is:

$$x_h = \frac{1}{h}\left(x_{ob} - (1-h)\frac{d_{ob}^2 + R^2 - h^2}{2d_{ob}^2}\left(x_{ob} \pm y_{ob}\sqrt{\frac{4R^2 d_{ob}^2}{d_{ob}^2 + R^2 - h^2} - 1}\right)\right)$$

$$y_h = \frac{1}{h}\left(y_{ob} - (1-h)\frac{d_{ob}^2 + R^2 - h^2}{2y_{ob}}\left(1 \pm \frac{x_{ob}}{d_{ob}^2}\left(x_{ob} \pm y_{ob}\sqrt{\frac{4R^2 d_{ob}^2}{d_{ob}^2 + R^2 - h^2} - 1}\right)\right)\right)$$

If instead of having a punctual obstacle we have an object (or several of them), we must simulate all these possible movements for all the points of the object, obtaining a set of orange trajectories, each one related to a point of the object where it can hit the arm.

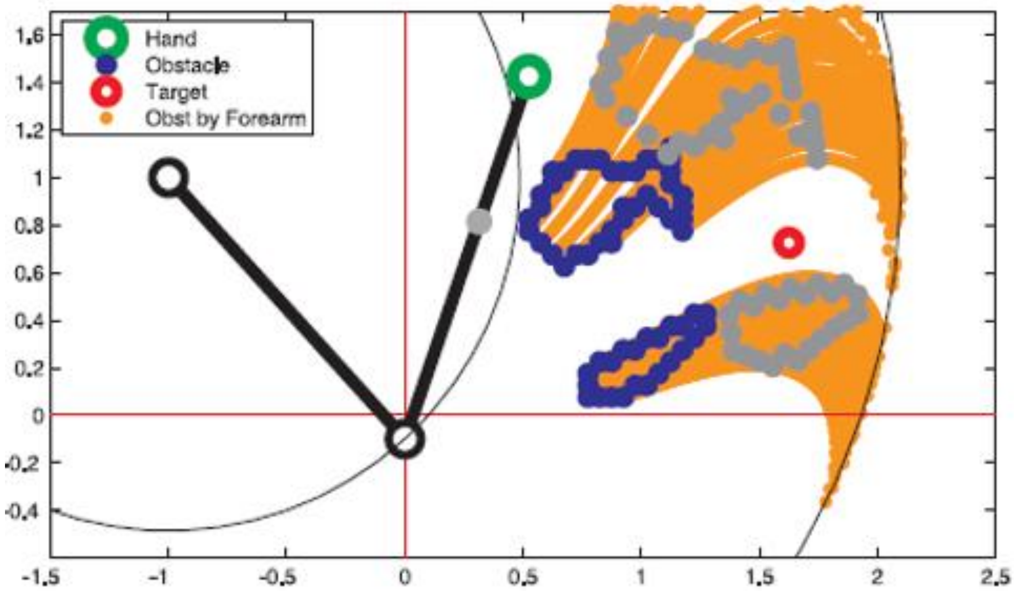


***Figure 13**: Extended obstacle (orange lines) of obstacles (blue figures). Grey figures are effective obstacles of obstacles when we fix a collide point in the arm (grey point).*

This way, for every blue point of the obstacle against which the arm can collide, we have a trajectory of orange points that represent all the positions of the hand associated with the impact of the arm with the blue point of the obstacle. The gray drawing of the obstacle superposed to the orange trajectories is just the position of the hand when the gray point of the arm clashes with the obstacle.

If we make the simulation to obtain the corresponding CCM we obtain:

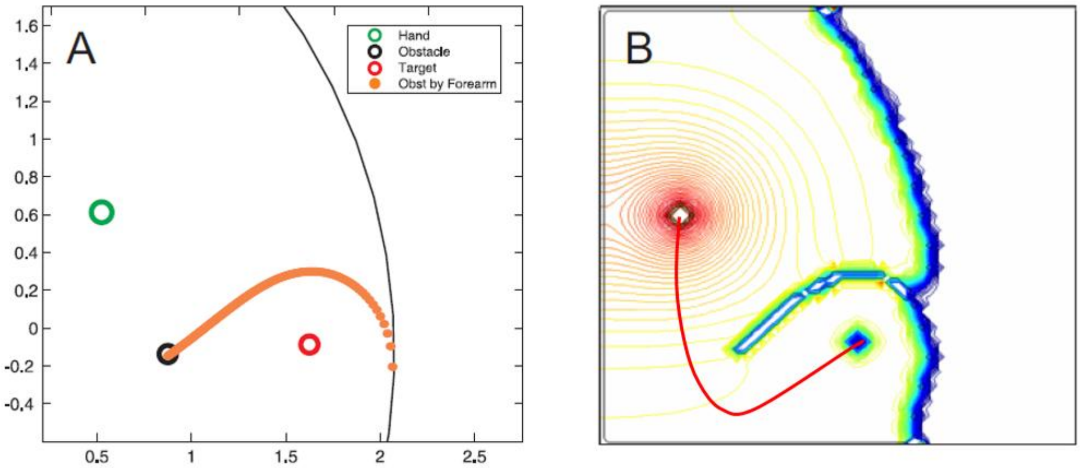


Figure 14: *Simulation in Matlab to obtain the CCM*.

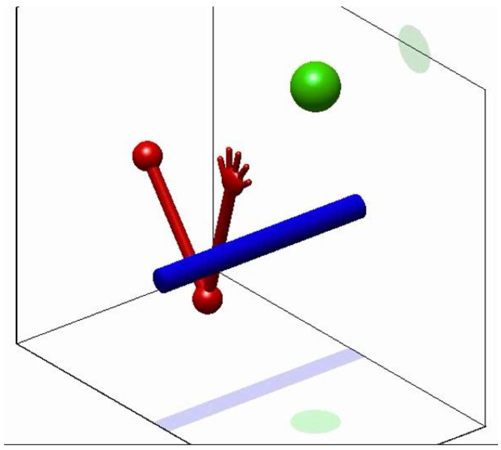


Figure 15: *3D representation when the target is not a point*.

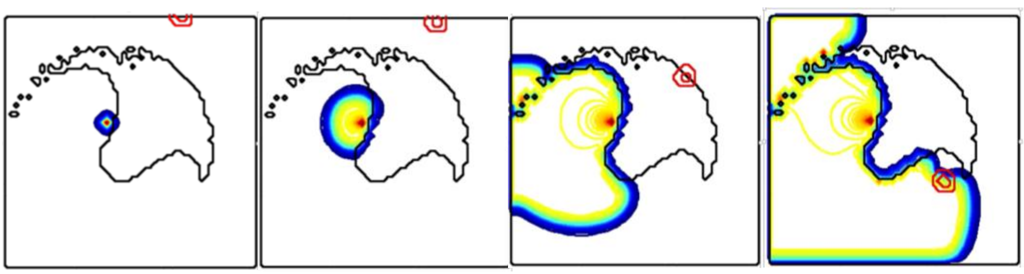


Figure 16: *Six frames from the simulation in Matlab to obtain the CCM in the 3D case.*

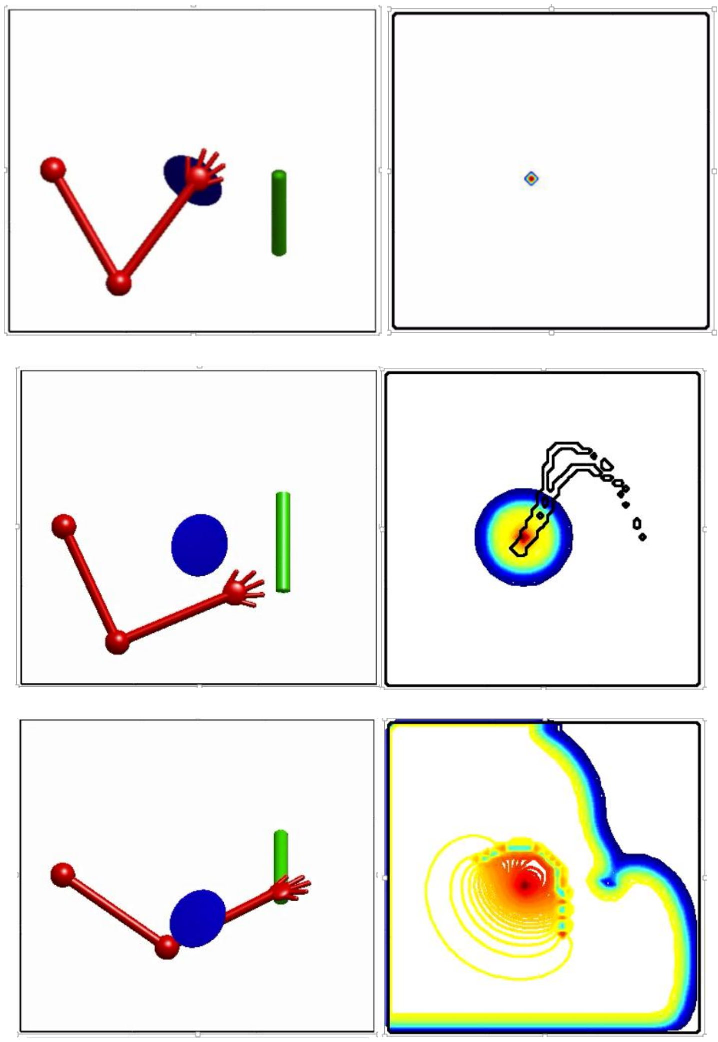


***Figure 17**: Three frames from Matlab (right frames) and 3D representation (left frames) to obtain the CCM about a dynamic situation in manipulation.*

8. Summary.

- The Compact Cognitive Map **permits to represent a dynamic situation as a static cognitive map.**

- **CCMs support artificial cognition** since they permits the understanding of dynamic situations. Moreover is serves as a natural substrate for memory and learning.

- The CCM permits to **unify the main types of robot interaction under a common theoretical framework** of cognition (navigation, manipulation and versatile locomotion).