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Collective Behaviors in Swarms of Builder Robots

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Abstract. Swarm robotics is inspired by the behavior of social animals for the coordination of a large number of low cost and insufficient robots that in performing a task requires collaboration. The behavior in a swarm of robots can be manipulated by changing the parameters of repulsion, attraction, orientation and influence (RAOI). In the case of repulsion, attraction and orientation modify the basic behavior of the swarm creating functional groups of robots keeping them close or dispersed, even forming chains. While the influence parameter is associated with specific stimuli to guide the swarm to perform simple tasks. To demonstrate this, a simulation platform presents the impact of these parameters in a swarm of builder robots considering a task of transporting materials.

Keywords: collective behavior, collective construction, builder robots, swarm robotics, robotics in construction.

1 Introduction

There is a widespread trend in the use of small low-cost robots rather than a single robot for certain tasks of exploration, localization, formation generation, etc [1,3,5,7,14]. Robot coordination is inspired by the behavior of social animals such as insects and mammals [10]. When multiple individual organisms meet and move as a coordinated entity is called a swarm.

Swarm behavior also allows groups of animals to accomplish tasks they could not solve individually. This leads to enormous advantages over a single individual because it allows him to solve problems in parallel and the exclusion of some members does not imply a deterioration in the elaboration of task [4].

A swarm of robots is constituted by simple robots with sensory limitations of perception at the local level that follows very simple rules. However, when interacting with the nearest neighbors or through indirect signals, very complex behaviors emerge that can be governed to perform complex tasks such as those required under construction [12,13].

Inspired by the behavior that exists in swarms, herds, hordes, etc. and considering builder animals such as bees, termites, beavers to name a few, rules of behavior can be proposed to govern a swarm of building robots to perform construction tasks using the information they collect in their environment [8].

In literature, swarms of robots are structured to work with a single type of material, in other cases, the materials are sensors or marks inserted to help robots identify objects. On the other hand, both robots and materials are structured so that they can perform the construction [11]. In our case, we try not to structure the robots or materials. The objects that can be gripped by each robot depends on the maximum opening of the gripper and the size of each object, therefore we only deal with small objects. The challenge of the project lies not so much in the hardware but the software because it is necessary to modify the equations inspired in the computation of swarms to create local behavior policies without relying on the position of each robot but to use only the local information that each member of the swarm.

The motivation is to develop behavior rules that are based on the repulsion, attraction, orientation and influence parameters and local information to perform construction tasks such as transporting materials, their location and placement. The proposed method is not based on centralized control and does not require to know the exact (Cartesian) position of swarm members. We selected metrics of search time and delivery, and the distance reached by the robots to evaluate the performance of the swarm.

2 Kinematics and Dynamics Model

To represent each member of the swarm through simulations, it is considered a mobile robot with differential configuration. Based on the work of A. Bara [2], the kinematics and dynamics of swarm members are described by the expressions (1) and (2), respectively:

$$\begin{bmatrix} \dot{x}_g \\ \dot{y}_g \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \frac{r}{2}\cos(\theta) - \frac{rd}{2R}\sin(\theta) & \frac{r}{2}\cos(\theta) + \frac{rd}{2R}\sin(\theta) \\ \frac{r}{2}\sin(\theta) + \frac{rd}{2R}\cos(\theta) & \frac{r}{2}\sin(\theta) - \frac{rd}{2R}\cos(\theta) \\ \frac{r}{2R} & -\frac{r}{2R} \end{bmatrix} \begin{bmatrix} \omega_r \\ \omega_l \end{bmatrix}, \tag{1}$$

where θ is the orientation the center of mass G of the mobile with respect to the inertial frame $\{I\}$, ω_r and ω_l are the angular velocities applied to the right and left wheels, d is the length between the center of mass G and the origin of mobile frame $\{M\}$, r is the wheel radius, R is the length between wheel and origin C of mobile frame and, finally, x_c and y_c are the cartesian coordinates that determine the position of the origin C of mobile frame.

$$\begin{bmatrix} m & 0 \\ 0 & I + md^2 \end{bmatrix} \dot{\mathbf{v}} + \begin{bmatrix} -md\dot{\theta}^2 \\ mdv_c\dot{\theta} \end{bmatrix} (\mathbf{v}) = \begin{bmatrix} \frac{1}{r} & \frac{1}{r} \\ \frac{R}{r} & -\frac{R}{r} \end{bmatrix} \tau, \tag{2}$$

where m is the mass of robot, I is the inertia moment, $\mathbf{v} = [v_c\ \dot{\theta}]^T$ is the vector of velocities, and $\tau = [\tau_r\ \tau_l]^T$ is the vector of wheel torques.

3 Behavior Rules

Behavior rules are based on mathematical equations that have four parameters that are associated with specific behaviors. In repulsion the robot seeks to move away from its neighbors to avoid collisions, in attraction the robot seeks to approach other members of the swarm, in orientation the robot aligns in the direction of its neighbors and with influence the robot associates a stimulus with a specific task that in our case is the execution of simple construction tasks [9]. To design new rules of behavior, different influence signals are associated with specific stimuli that are detected by different sensors.

The repulsion, attraction and orientation radius are represented by r_r, r_o and r_a, and limit the local zones shown in figure 1, where the robot is in the center of the zones [6].

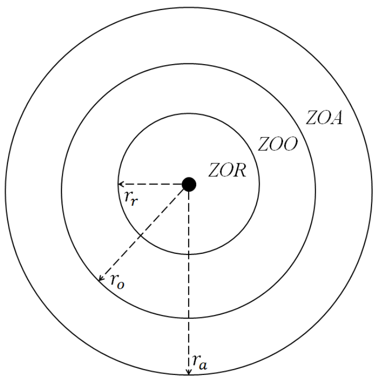
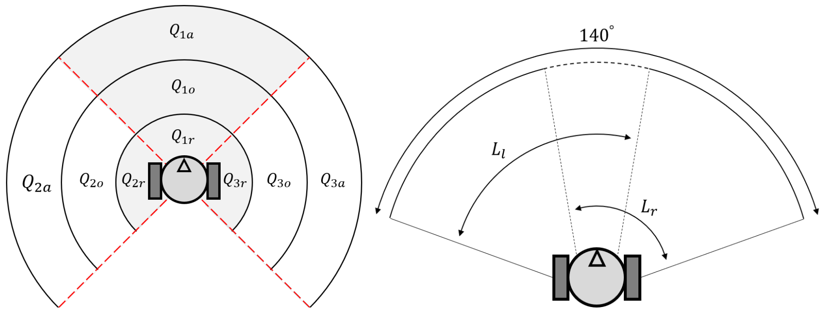


Fig. 1. Zones of repulsion (ZOR), orientation (ZOO) and attraction (ZOA).

Each member is provided with proximity and light sensors to detect and measure the distance with neighbors or objects and get information from the light perceived in the environment. These sensors are located at the front, left and right of the robots. Also, they are equipped with a gripping mechanism for holding and transporting objects

The location of the sensors allows zones in figure 1 to be divided into new sections shown in figure 2. In this work only the Q_1a, Q_1o, and Q_kr, with $k = 1, 2, 3$, zones are considered. The Q_1a zone is the only one that allows the robot to be attracted with its neighbors, the Q_1o zone keeps the robot in its current direction and the Q_kr zones evade their neighbors to avoid collisions. Besides, L_l and L_r are the light detection zones perceived by the left and right sensors respectively.

Because of sensory limitations, robots only have information about an approximate distance from their neighbors or objects in direction of the corresponding proximity sensor. There is no information about orientation or the number



(a) Repulsion and attraction zones detected by distance sensors (b) Light detection zones by photoresists

Fig. 2. Perception zones by sensors for each robot.

of neighbors, and the allowed movements in the robots are turns in their axis and forward.

When a robot detects neighbors in ZOR, it decreases its speed and changes its direction relative to the equation 3. If it does not detect other robots in ZOR, the orientation is governed by the influence detected in the environment.

If the gripping mechanism is open, the robot searches for objects placed in the test area guided by the influence, otherwise it deposits them in the collecting area. If it detects neighbors in ZOA, it increases its speed in its current direction (equation 4). These rules return according to the status of each robot.

Where d_r and d_a represent the direction vector of robot in ZOR or ZOA, respectively.

$$d_r = -(q_{1r}[1,0] + q_{2r}[0,1] + q_{3r}[0,-1]), \tag{3}$$

where

$$q_{kr} = \begin{cases} 1, & \text{if neighbors are detected in } Q_{kr} \text{ zone,} \\ 0, & \text{if neighbors are not detected in } Q_{kr} \text{ zone,} \end{cases}$$

$$d_a = q_{1a}[1,0], \tag{4}$$

where

$$q_{1a} = \begin{cases} 1, & \text{if neighbors are detected in } Q_{1a} \text{ zone,} \\ 0, & \text{if neighbors are not detected in } Q_{1a} \text{ zone.} \end{cases}$$

4 Simulation Environment

4.1 Experimental Setup

Experiments based on simulations were carried out to understand the effects of repulsion, attraction, orientation and influence on the swarm. Simulations were performed with 5, 10 and 20 robots with differential configuration and 20

Table 1. Robot parameters.

Parameter	Value
m	$0.325kg.$
I_p	$0.005kg \cdot m.^2$
r	$0.03m.$
R	$0.05m.$
d	$0.02m.$
$c_r = c_l$	$0.434\ s$
$k_{L,r} = k_{L,l}$	$2.745\ \frac{rad}{s \cdot N-m}$
$k_{s,r} = k_{s,l}$	$1460.2705\ \frac{rad}{s \cdot V}$

randomly placed objects in an area of 10 x 10 m, the physical parameters of the robots are shown in table 1. The object location zone is at coordinates [7.5, 7.5] and has a radius of 4 m, while the delivery zone is at coordinates [2, 2] and has a radius of 4 m. These experiments were performed on Scilab 6.0.1 software on Intel(R) Core(TM) i7-7500U CPU 2.9 GHz, RAM 8GB and 64-bit operating system.

4.2 Object Transport Task

The experiment consists of a task of transporting objects, considering a limited area and randomly placed objects, the goal is to collect these objects and group them in the desired zone. Dynamics of simulated robots are governed by RAOI parameters and environmental conditions. The influence factor helps robots to find objects by giving an approximation of their location, as they cannot be detected unless they are a minimum distance away. When a robot collects an object, a new stimulus moves it to the desired zone. This allows the main task to be divided into search and delivery subtasks. The stimuli are generated by a simulated light source in the environment. The simulation ends when the robots deposit all objects in the desired zone.

In these experiments, all members of the swarm are given the same parametric settings. Tables 2 and 3 show an experimental design for changes to parameters. In the parametric settings of the table 2, the values of r_o and r_a are set as constants and only r_r varies, while in the table 3 r_e and r_o are set as constants and only r_a varies. This is to explore the behavioral changes that arise when values of repulsion and attraction change. Three replicas were performed for each experiment to complete 54 tests. Table 4 shows the speeds of the robots when in a specific zone.

5 Results and Discussions

To illustrate the swarm's performance, graphics simulations are carried out. The figures 3 and 4 show some snapshots of a simulation with 20 robots and 20 objects. The robots are represented with black arrows when they look for objects

Table 2. Parametric settings changing repulsion values with $r_o = 0.15$ and $r_a = 0.2$ as constants.

Objects	Robots	Repulsion radius (m)
20	5	0.01
		0.05
		0.1
	10	0.01
		0.05
		0.1
	20	0.01
		0.05
		0.1

Table 3. Parametric settings changing attraction values with $r_r = 0.05$ and $r_o = 0.15$ as constants.

Objects	Robots	Attraction radius (m)
20	5	0.2
		0.6
		1
	10	0.2
		0.6
		1
	20	0.2
		0.6
		1

Table 4. Speeds in perception zones.

Zone	Speed (cm/s)
Repulsion	5
Orientation	10
Attraction	$(v_i + 20)/2$
Influence	10 - 20
Out of range	10

and blue when they deliver them, while objects are represented with yellow circles. These figures give us a visual perspective about the behavior of the swarm through perform task time.

The swarm of figure 3 has low repulsion values and high attraction. In this configuration the object collection is constant, that is to say, in the snapshots times shown there are always robots searching and delivering objects. Robot chains of different lengths are formed, this helps the robots to reach the object search zone more quickly, however, sometimes these chains are headed by robots that are in their delivery task and divert attention from those that are in a search task. On the other hand, the swarm of figure 4 has high repulsion and low attraction values. Unlike the previous configuration, the swarm's behavior is more closely joined and causes most objects to collect at first. However, the behavior is cycled when the swarm revolves around the last objects. When robots search objects, they converge to them through influence. In some cases, one or two robots are separated from the swarm because they aren't detecting objects but finally converge towards them.

Tables 5 and 6 show results of experiments performed with parameter settings from tables 2 and 3, respectively in a average scenario. Best-performing results are marked in bold for each swarm population size. A better perspective to the results is shown in figures 5 and 6.

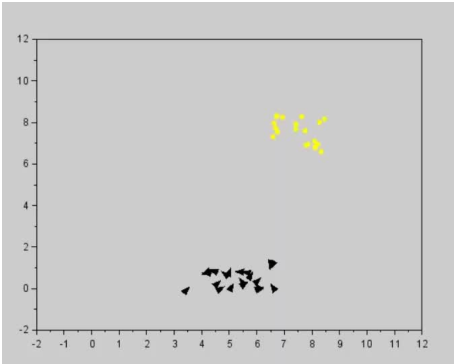
Table 5. Swarm behavior by changing repulsion values.

Robots	Repulsion radius (m)	Delivery time (s)	Search time (s)	Time (s)	Distance reached (m)
5	0.01	**797**	6966	7763	913.38
	0.05	801	9380	10181	1099
	0.1	865	**4364**	**5229**	**590**
10	0.01	413	**2117**	**2530**	**262.47**
	0.05	**382.47**	4542	4925	548.15
	0.1	390	3149	3539	377.94
20	0.01	**199**	1877	2076	221.44
	0.05	201	2012	2213	233.13
	0.1	381	**680**	**1061**	**79.68**

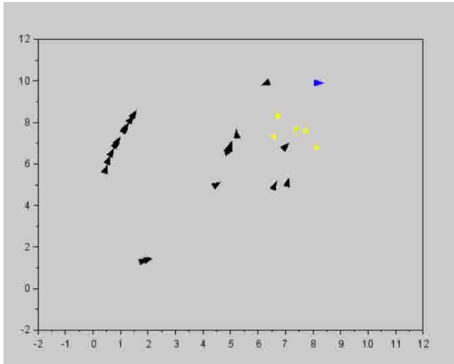
Table 6. Swarm behavior by changing attraction values.

Robots	Attraction radius (m)	Delivery time (s)	Search time (s)	Time (s)	Distance reached (m)
5	0.2	801	9380	10181	1099.12
	0.6	793	**3070**	**3863**	**392.15**
	1	**781**	5450	6232	588.16
10	0.2	**382**	4542	4925	548.15
	0.6	393.80	**3129**	**3522**	**379.44**
	1	395	4209	4604	510.32
20	0.2	201	2012	2213	233.13
	0.6	207	**914**	**1121**	**111.93**
	1	**195**	1517	1711	178.70

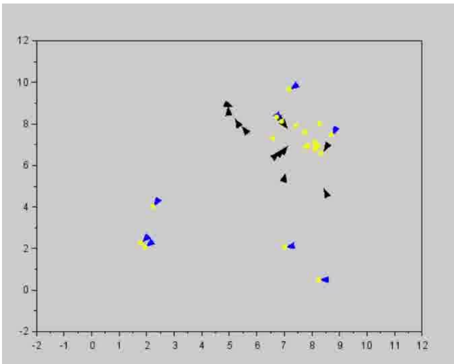
The results in figure 5 show that with average repulsion values the swarm performs worse, while at the extremes (low and high repulsion) the swarm performs its tasks faster and with better performance. The results in figure 6 show the opposite behavior but with attraction values. With average values,



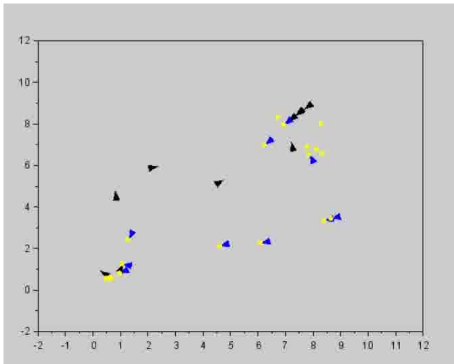
(a) $0s$



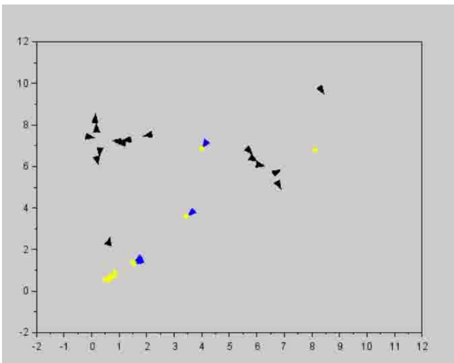
(b) $224s$



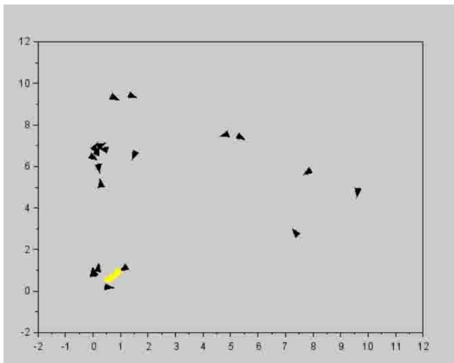
(c) $448s$



(d) $672s$



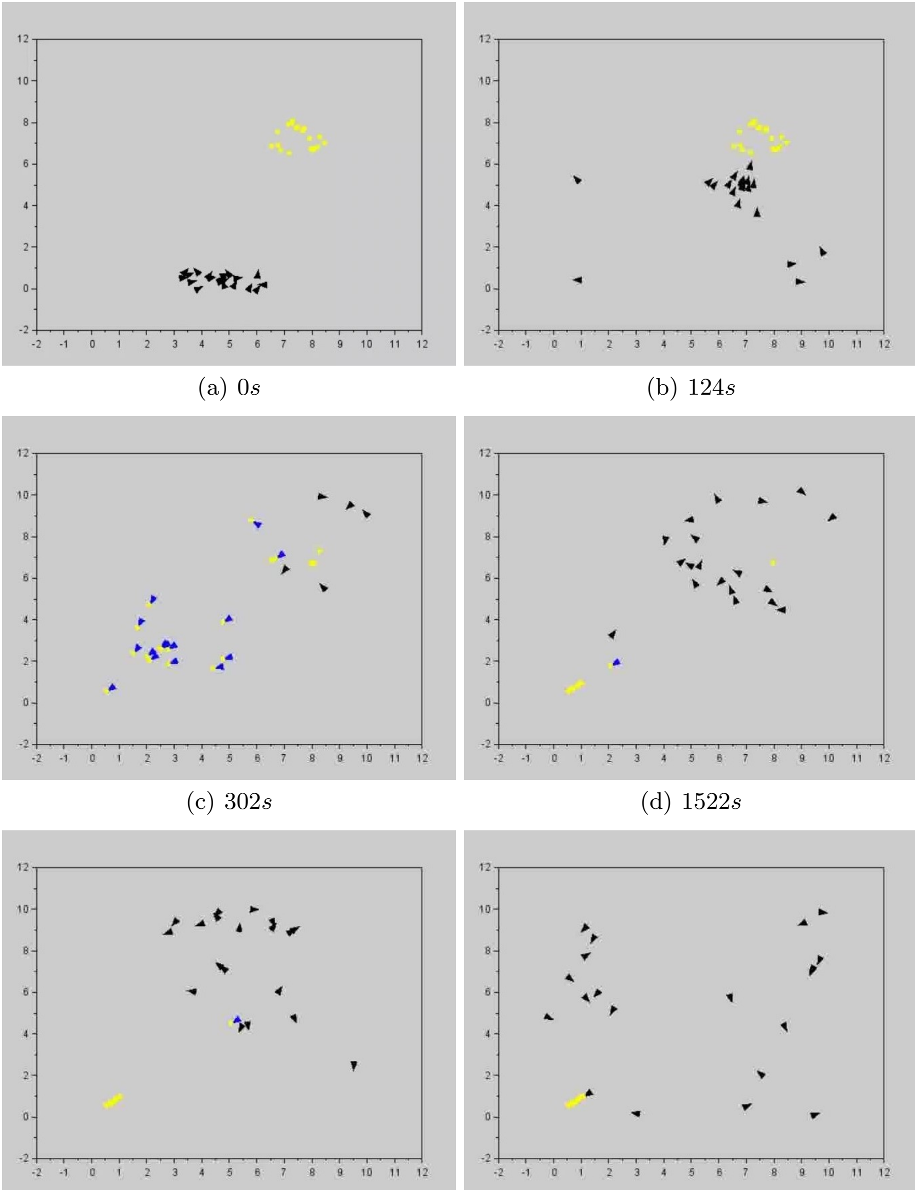
(e) $896s$



(f) $1126s$

Fig. 3. Swarm simulation with 20 robots performing an object transportation task with $r_r = 0.01$ and $r_a = 1$.

better performance is obtained concerning low and high values. In both cases, as the population size increases, these properties remain but their intensity



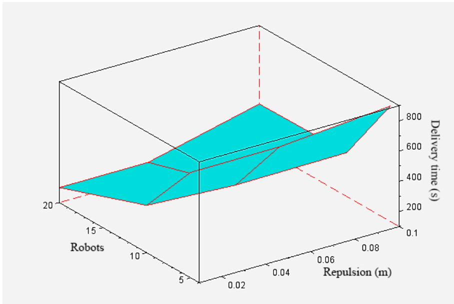
(a) 0s (b) 124s

(c) 302s (d) 1522s

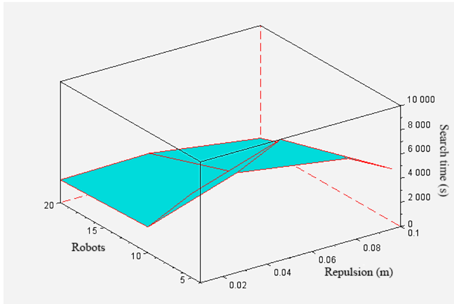
(e) 2154s (f) 2356s

Fig. 4. Swarm simulation with 20 robots performing an object transportation task with $r_r = 0.1$ and $r_a = 0.2$.

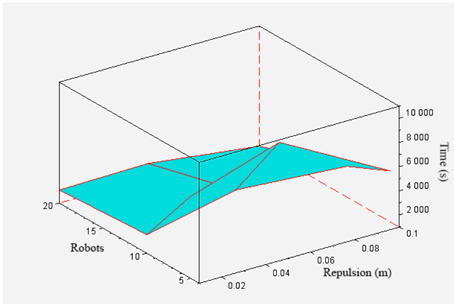
decreases. However, the measurements showed only reflect a change in behavior through parametric variations but formation properties or how robots achieve



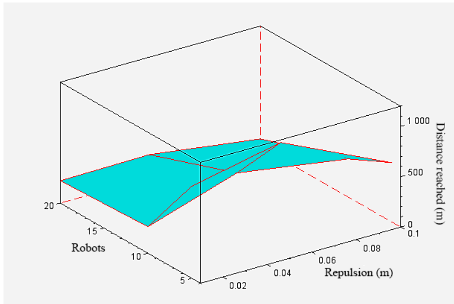
(a) Delivery time



(b) Search time



(c) Time



(d) Distance reached

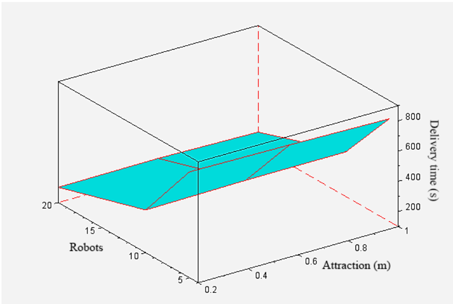
Fig. 5. Swarm behavior by changing repulsion values.

their objectives are explained below based on the snapshots of figures 3 and 4. When repulsion is low, robots tend to hold together to avoid collisions. As repulsion increases, they disperse and have priority to remain away from their neighbors rather than collect objects. A high attraction causes chains of robots to form, this causes collisions between them to be avoided and reach their goal more easily

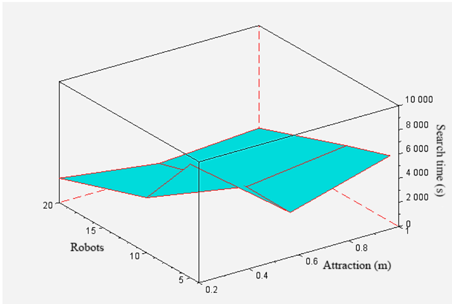
6 Conclusions and Future Work

Different parametric settings were explored through simulations by changing the repulsion and attraction parameters, through these changes it is demonstrated that it is possible to govern the swarm behavior to perform search and delivery tasks more effectively. However, these parameters have not been fully explored because while one changed the others remained constant. Due to the stimuli received by the robots in the environment it is possible to switch the parameters concerning each sub-task to reduce the total time of the main task.

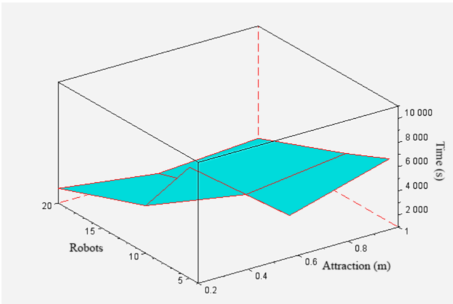
Although these rules have already been explored by simulation for construction tasks, they have not yet been implemented in real robots. Even though there are swarms of builder robots in the literature, they are still very structured, so as a future work we propose the development of a more open platform generating



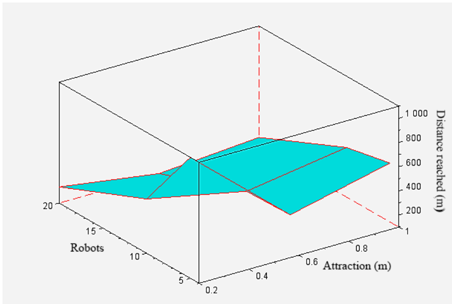
(a) Delivery time



(b) Search time



(c) Time



(d) Distance reached

Fig. 6. Swarm behavior by changing attraction values.

technology and own designs implementing these rules to a swarm of builder robots. In addition to this, it is desired to test more parametric values to generate new behaviors that have not yet been explored and to change these values according to subtasks they perform when perceiving factors of influence in environment.

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