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The Cart-bot and the Cooperative Transport of Multiple Objects in the Swarmanoid Project

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Abstract

In this paper we present an approach to the cooperative transport of multiple objects in swarm robotics. The approach is motivated by the observation that the performance of cooperative transport in insect colonies as well as in groups of robots grows in a super linear way with the number of individuals participating in the transport. The approach relies on a cart in which multiple objects are collected and stored before being transported to destination. The cart is moved by a group of robot that would be otherwise allocated to the transport of single objects. The cart is endowed with computational and communication abilities that allow it to cooperate with the transporting robots. This research is carried out within the framework of the Swarmanoid project and aims at enhancing the transport capabilities of the robot swarms developed in this project.

1 Introduction

Cooperative transport is a classical problem studied in the collective robotics literature [1, 2, 3, 4, 5]. Robots have to perform cooperative transport when a task requires the transport of an object that a single robot is not able to handle and move. Approaches to solve this problem have typically taken inspiration from biological systems, especially from colonies of social insects [6, 7, 8].

In particular, ant colonies display two different transport behaviours: solitary transport and group transport. In some ant species, group transport is observed when a prey is larger or heavier than the transporting capability of a single ant. In this case, ants have the options either to cut the prey in pieces and to transport each piece individually, or to cooperate to transport the whole prey in group. Studies show that transporting the prey as a whole in group is usually more efficient than the solitary transport of pieces [9, 10].

Kube and Zhang developed a model of cooperative transport inspired by the behaviour of socials insects [7]. The accuracy of this model was then demonstrated by Kube and Bonabeau with experiments involving a group of real robots [11]. Additional experiments have shown that transport performance grows in a super linear way with the number of robots, which is similar to what is observed with ants [12, 13].

In this paper, we present an approach to enhance the ability of a group of robots to transport objects cooperatively. The objects to be transported are gathered in a cart and are then transported collectively as a single entity. The research presented in this paper is carried out within the framework of the *Swarmanoid* project [14], a Future and Emerging Technologies (FET-OPEN) project funded by the European Commission. The goal of the project is to develop a *swarmanoid*, that is, a swarm-based alternative to a humanoid robot. In a *swarmanoid*, the functionalities that one typically expects in a humanoid robot are distributed among the individuals of an heterogeneous swarm of robots. The *swarmanoid* is composed by a number of *eye-bots*, which are flying robots that are able to explore a scene and to localize objects; by a number of *hand-bots*, which are manipulators that are able to climb and to grasp object; and by a number of *foot-bots*, which are robot rovers that are able to move on the ground and to transport objects or other robots. In the spirit of the *Swarmanoid* project, we define a fourth kind of robot: the *cart-bot.* A *cart-bot* is able to store a number of objects, to cooperate with hand-bots in order to facilitate the loading and unloading of objects, and to cooperate with foot-bots to ease its own transport.

The rest of the paper is organized as follows: in Section 2 we detail the integration of the *cart-bot* in the *Swarmanoid* project. In Section 3 we describe the final design of the *cart-bot* hardware. In Section 4 we present the specific software we developed for simulating the *cart-bot* and its interactions with the other robots of the *Swarmanoid* project. Finally, in Section 5 we conclude the paper.

2 Integration of the *cart-bot* in the Swarmanoid project

The *Swarmanoid* project is developed around a main scenario, which illustrates the use of morphologically specialised robots to solve a complex mission in a human-like environment. In the following, we describe how the *cart-bot* can be used to enhance transport tasks in the scope of this scenario.

In the *Swarmanoid* scenario, an heterogeneous group of robots is employed to locate books situated on shelves, collect them, and bring them to a target place. For practical reasons, rather than with real books, robots deal instead with models of books that we call *book-bots.* A *book-bot* is made of foam so that it causes less damages if it inadvertently falls on the ground or on a robot; moreover, it features a number of LEDs on the spine to facilitate its localisation.

A typical unfolding of the scenario is as follows: first the *eye-bots* explore the environment. Once they have located a number of *book-bots*, they guide other robots to them. The *hand-bots* that have extended manipulation capabilities are transported by the *foot-bots* close to these *book-bots.* The *hand-bots* get a hold of the *book-bots* one by one. In a scenario without the *cart-bot*, each *book-bot* is transported by a system composed of a *hand-bot* holding a *book-bot* and a number of *foot-bots* carrying the *hand-bot.*

With the *cart-bot* included in the scenario, once a *hand-bot* grasps a *book-bot*, it lays it on the depository area of the *cart-bot*, as shown in Figure 1(a). The *cart-bot* automatically swallows the *book-bot* to store it inside his rack and the *hand-bot* is therefore free to pursue the collection of another *book-bot.* As soon as the *cart-bot* is full or has loaded the required number of *book-bots*, it advertises to surrounding *foot-bots* that it is ready to be transported. Once *foot-bots* are physically connected to the *cart-bot*, it lifts up the part of its body that was previously in contact with the floor— see Figures 1(c) and 1(d). By doing this, the *cart-bot* prevents any friction with the ground, therefore facilitating its transport. Eventually, the *cart-bot* communicates with the connected *foot-bots* to let them know that transport can be performed at any time.

The integration of the *cart-bot* in *Swarmanoid* allows to study stacked transport against single transport of multiple objects. Furthermore, contrary to the *hand-bot*, the *cart-bot* is specialized for transport: it is able to store a number of *book-bots*, it has no fragile external components like manipulators do, *book-bots* are stabilized inside the *cart-bot* and may not fall on the floor. Lastly, the *cart-bot* is large and *foot-bots* can connect to it all around such that the resulting assembly is very stable.

3 Hardware design

The two main functionalities of the *cart-bot* are storing *book-bots* in a single rack and allowing the single cooperative transport of all the gathered *book-bots* by the *foot-bots.* The design of these

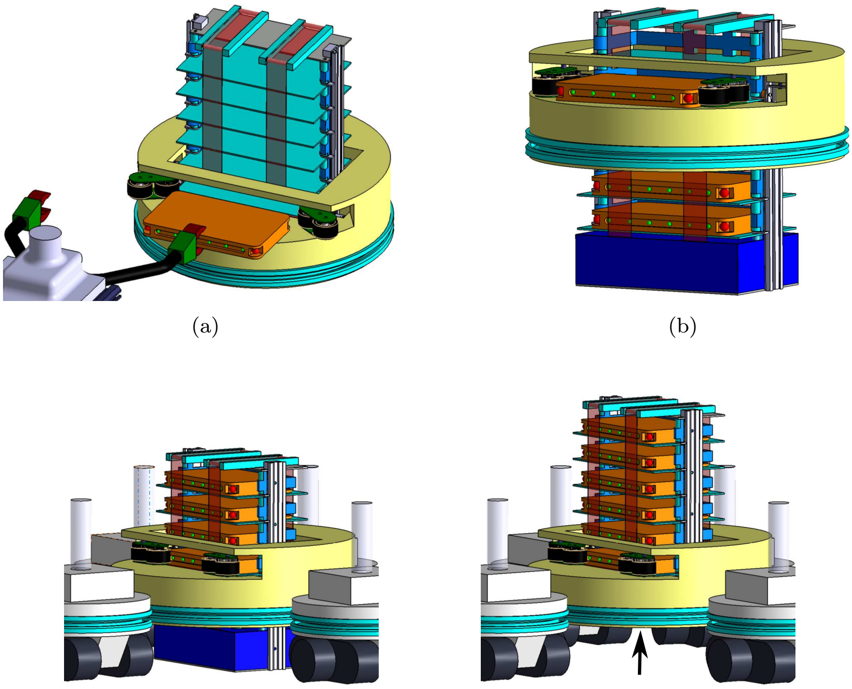
(a) (b) (c) (d)

Figure 1: (a) *Book-bot* put on the loading bay by a *hand-bot*. (b) Base elevation on the rack to reach a high slot. (c) *Foot-bots* docked to the *cart-bot*. (d) Rack elevated to remove friction with the ground.

functionalities are described in the following.

3.1 Storing ability

In order to store the *book-bots*, the *cart-bot* introduces them inside the slots of a storing system called the *rack*. This can be done in two different ways: either by having the *hand-bot* inserting a *book-bot* directly in a selected slot, or by having the *hand-bot* laying a *book-bot* down in an apposite bay and then moving the *book-bot* to the appropriate slot through some loading and unloading mechanisms. The second approach turns out to be simpler to implement and requires less accuracy in the positioning of the *book-bot* by the *hand-bots*.

In the design we developed, the loading and the unloading functions are carried out by a single mechanism. This loading/unloading mechanism consists of two rotating arms with wheels at their ends. The arms are located on both sides of the loading bay, right in front of the slots as it can be seen in Figures 2(a), 2(b), 2(c) and 2(d). By rotating in one direction or in the opposite, these rotating arms can reach a *book-bot* either when the *book-bot* is on the loading bay—as shown in Figure 2(a)—or when the *book-bot* is inside the slot—as shown in Figure 2(d). In particular, Figure 2(b) shows how the arms, pressed against a *book-bot*, push the *book-bot* itself inside the slot. The wheels turn and push the *book-bot* in the same direction. This always ensures a tight contact and a good grip with the *book-bot*. Once the *book-bot* has been swallowed by the wheels, the arms complete their rotation and push the *book-bot* inside the slot to their final storage position—as shown in Figure 2(c).

During the loading phase, the trajectory followed by the *book-bot* is determined by the angular position of the arms. In particular, in order to insure that the *book-bot* enters the slot with a correct angle, the rotating arms must assume a symmetric angular position. During the whole

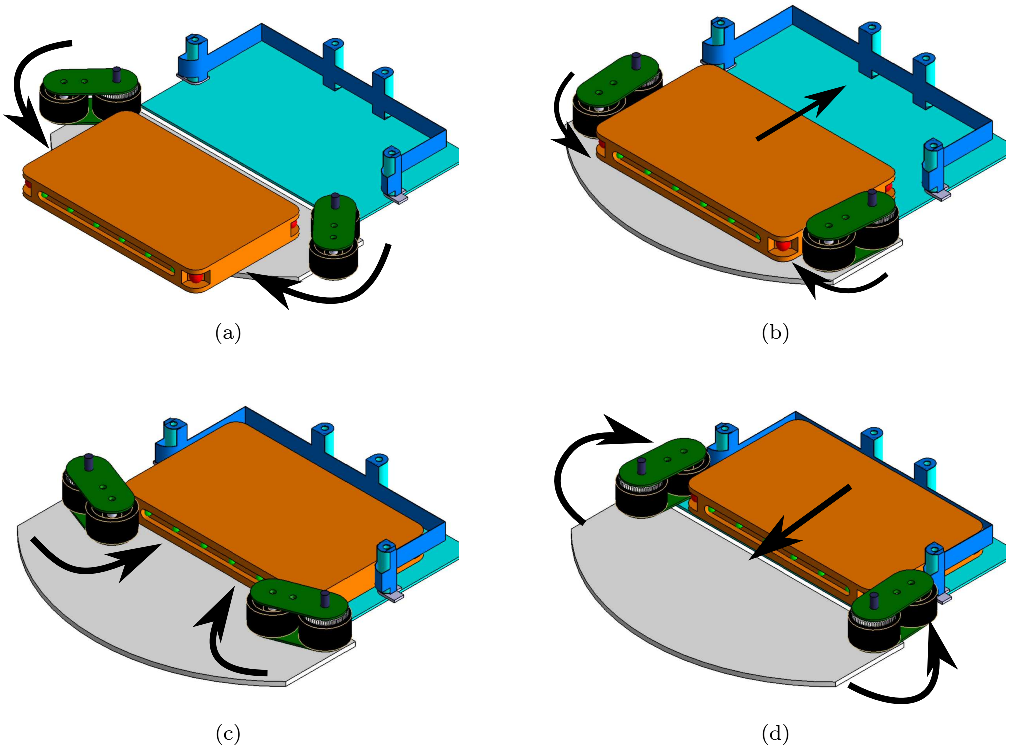
(a) (b) (c) (d)

Figure 2: (a) The arms rotating to a *book-bot* on the loading bay. (b) The wheels pushing the *book-bot* inside a slot. (c) The arms finishing to push the *book-bot* in the slot. (d) The arms reversed to get a *book-bot* from a slot.

procedure, the speed and the direction of the motors are adapted in order to correct the trajectory of the *book-bot*. If an incoming *book-bot* gets stuck, the failure is detected by a current peak on the blocked motor or by the incomplete angular positioning of the rotating arms. The motors are reversed and the whole procedure is repeated.

The slots where the *book-bots* are stored are engineered in a way that they form a vertical rack of horizontal slots—see Figure 1(a). The storing system manages the slots and takes care to align the loading bay and the loading/unloading system with the slot in which the *book-bot* has to be inserted. In order to achieve correct alignment, the rack can be moved relatively to the base platform or the opposite, depending on whether the *cart-bot* is being held by *foot-bots* or whether it lies on the ground—see Figure 1(b). This allows the system to lift up the rack and ease transport by preventing any friction with the ground, as described in the subsection 3.2.

The structure of this system is well adapted for a classical elevator type regulation and is very similar to an elevator architecture. It uses linear guides and a timing (toothed) belt—see Figure 3(a). The belt is driven by a pulley fixed directly on the shaft of a motor with an encoder. The belt transmission was preferred to a screw drive transmission because of weight and efficiency concerns, but it has the drawback of not being auto-blocking. This leads us to implement a braking system that insures precise alignment of the slot to the loading bay. It is designed to be finely adjustable in height and is based on simple and lightweight components—see Figure 3(b).

The presence of a *book-bot* in a slot is perceived as the success of the loading and is memorized by the storing system. To ensure a reliable perception of the status of the slots, we introduce redundancy with optical sensors. This information is critical to know where are the free slots and when the *cart-bot* is ready to be transported.

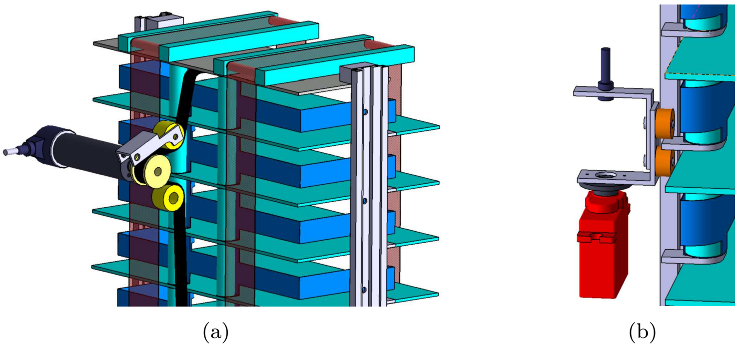

Figure 3: (a) Belt transmission and linear guides. (b) Brake mechanism on a slot.

3.2 Transportability

To display its status, for example when it is ready to be transported, the *cart-bot* uses a ring of RGB LEDs. This color ring can also be used coordinate the *foot-bots* by indicating them in what position they should dock. Docking is achieved by the the *foot-bots* by gripping a docking ring on the *cart-bot*. This docking ring is positioned on the lowest part of the base platform. The *cart-bot* uses the mechanism of the storing system to elevate the ring up to the height of the gripper of the *foot-bots*. This prevents the ring to be in the way of a *book-bot* brought horizontally by a *hand-bot* to the loading bay when the base platform is lowered—see Figure 1(a).

During all these manipulations the rack of slots is resting on the floor. It presents high resistance to the *foot-bots* trying to push or pull it. Docked *foot-bots* may rely on this resistance to decide to recruit more *foot-bots*, as exposed in [15]. Once enough *foot-bots* are docked, the rack is lifted up so that it doesn't touch the floor anymore and the friction to the ground is canceled—see Figure 1(c). Thanks to this mechanism, the *cart-bot* has a good ground clearance when transported. The system formed by the *cart-bot* and the *foot-bots* is very stable with a large base and has a good mobility.

4 Software design

In order to ease the design of a controller for the *cart-bot* and for the robots that are supposed to interact with it, we have developed a set of simulation tools. The use of simulation to develop software for robots is a common practice and offers a number of advantages over working directly with the target hardware platform. In particular, simulation frees the developer from a number of concerns on the hardware such as limited battery life and mechanical faults, it reduces the risks of damaging the hardware with a preliminary controller, and dramatically reduces the development time.

The simulation environment adopted within the Swarmanoid project is called ARGOS [16] and has been developed within the framework of the project itself. ARGOS features an highly modular architecture: robot controllers, sensors, actuators, visualizations and physics engines are designed as plugins that the user can reuse and reimplement at will. In particular, the physics engine can be selected to meet the specific needs of each simulation. So far a number of physics engine modules have been developed including engines for 2D and 3D dynamic and kinematic simulation. See Figure 4 for a schematic representation of the architecture of ARGOS.

In order to simulate the *cart-bot* and its interaction with the other robots of the Swarmanoid project, we have implemented a new physics engine to be used within ARGOS. In particular, we have extended ARGOS so that the connection between *foot-bots* and the *cart-bot* is properly modeled via the physical laws of rigid body dynamics and that forces and torques are correctly

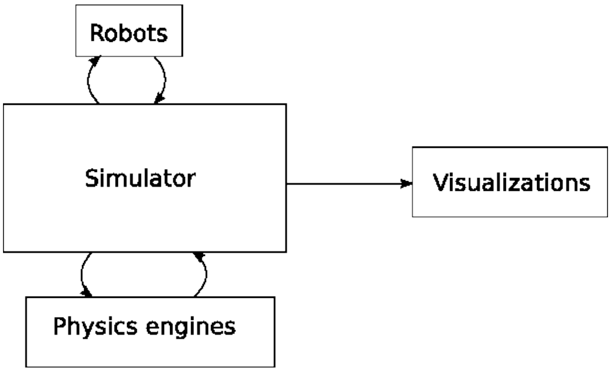

Figure 4: The design of ARGOS allow multiple physics engine and visualization.

taken into account.

We decided to focus our attention on the development of a two dimensional physics engine. The choice of simulating the interaction between the *foot-bots* and the *cart-bot* in two dimensions appears reasonable since the robots move on a flat area and have similar height. On the other hand, working in two dimensions rather than in three entails a significant speedup in the simulation.

The most characterizing design choice of the physics engine we have developed concerns the way we adopted to model the connections between robots. Indeed, since connections between *foot-bots* and *cart-bot* will be extremely frequent in the simulated experiments involving the *cart-bot*, they need to be handled in a very efficient way. For this reason we had to discard what is possibly the most frequently adopted and the most straightforward solution, that is, modeling the connection between two robots through a joint that imposes a constraint between the robots. Although effective, this solution appeared to be too much expensive from a computational point of view. As an alternative, we decided to follow the design choice of the TwoDee simulator [17]: When two robots connect to each other, they are merged into a new entity and are handled in the simulation as such till when they eventually disconnect. In this case, the physics engine needs to simulate only a single rigid body composed of multiple robots. This improves the whole performance of the simulation.

5 Conclusion

In the paper we have discussed the problem of the cooperative transport of multiple objects by a swarm of robots. In the approach we adopted, rather than transporting objects one by one, these are gathered in a cart which is subsequently transported by the swarm. With this approach, the transport performance grows super linearly with the size of the swarm, with the classic limitations induced by the problem of coordinating the movement of the swarm [12]. In the paper, we have analyzed the problem of transporting multiple objects within the framework of the *Swarmanoid* project. In particular, we have described the features and the design of the *cart-bot*, a robot which is able to store objects, the *book-bots*, and ease the task of other robots, such as the *foot-bots* that are intended to carry out transport.

The *cart-bot* enhances the robustness provided by the distributed hardware and control [18] in the transport of *book-bots*. The *cart-bot* secures the stored *book-bots* to avoid losing them during the transport due to collisions or to the roughness of the terrain. The large round shape of the *cart-bot* allows the *foot-bots* to dock all around it: this results in a very stable assembly. Moreover, the transporting assembly is little sensitive to terrain condition, thanks to a good ground clearance obtained through the elevation of the rack of the *cart-bot* after the docking with the *foot-bots*.

To ensure a robust transport, the *cart-bot* is designed to be simple and reliable. During transport, the *cart-bot* can be seen as a single resistant entity, as it has no fragile external parts.

The use of the same mechanisms for different functionalities minimizes the complexity and reduces the global weight of the *cart-bot*: rotating arms are used for loading and unloading and an elevation system is used for reaching different slots of the rack when loading and unloading and for elevating the rack itself during the transport. Finally, the *cart-bot* is mainly built with generic electronic and mechanical components, which makes the *cart-bot* easy to maintain.

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