COMPETITIVE DYNAMICS FOR BEHAVIOR COORDINATION IN A JOINT TRANSPORTATION TASK [1]

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Abstract: We address the problem of coordinating two non-holonomic mobile robots that move in formation while transporting a long payload. A competitive dynamics is introduced that gradually controls the activation and deactivation of individual behaviors. This process introduces (asymmetrical) hysteresis during behavioral switching. As a result behavioral oscillations, due to noisy information, are eliminated. Results in indoor environments show that if parameter values are chosen within reasonable ranges then, in spite of noise in the robots communication and sensors, the overall robotic system works quite well even in cluttered environments. The robots overt behavior is stable and smooth.

Keywords: motion coordination, mobile robots, payload/object transportation, collision avoidance, competitive dynamics, attractor dynamics.

1. INTRODUCTION

Joint transportation is a frequent task in many of our daily activities (Fig. 1) and as we probably have experienced ourselves motion coordination with our partner, which is essential for the success of the task, is not easy. The problem is even harder when we do not have a complete view of the environment we are moving in. Needless to say that in many applications it would be very useful if teams of autonomous robots could be used to transport long payloads. Specially in hazardous environments, places not yet reachable to humans (e.g. Mars), large distribution centers and large industrial plants. Thus many researchers and engineers working on cooperative robotics devote their efforts to this challenge(Ahmadabadi and

Fig. 1. Examples of joint transportation tasks

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Nakano, 2001; Asahiro *et al.*, 2001; Chaimowicz *et al.*, 2001; Kosuge *et al.*, 2000; Zaerpoor *et al.*, 2005; Wang *et al.*, 2004*a*; Wang *et al.*, 2004*b*; Zaerpoor *et al.*, 2005). Despite the efforts there are still many problems to be solved.

There are two general approaches for controlling multiple robots transporting an object: (1)- centralized control schemes and (2)- decentralized control schemes. The limited success of (1) is mainly due to communication costs, (2) is better but there is a major difficulty: the precise control and coordination of the robots is very difficult. From the point of view of a cooperating robot the environment, which consists of the manipulated object, the other robots and the world scenario (static or dynamic), exhibits complex dynamic behavior. The problem is exacerbated when the environment is unknown and no path is given.

In our approach we use leader-follower decentralized control strategies, and particular to our work, we use non-linear dynamical systems as a design and theoretical tool to design and implement the control architectures (Soares and Bicho, 2002; Bicho *et al.*, 2004; Soares *et al.*, 2007). The control architecture of each robot is structured in terms of elementary behaviors. Each behavior is modeled as a contribution to the vector field of the dynamical systems that generate the time course of the reference values to the control variables (heading direction and path velocity). Sensorial and/or communicated information is used to control activation variables that determine which component term of the vector field must dominate the dynamics.

In our previous work a non-linear static model was used to control the activation variables, i.e. their current values where made a function of the instantaneous values of the input variables. This raised, sometimes, the problem of oscillations during behavioral switch, due to limited sensors range and noise in the sensorial and/or communicated information. To overcame this drawback, we introduced a competitive dynamics, as reported in this paper, that gradually controls the activation and deactivation of individual behaviors. This process introduces (asymmetrical) hysteresis during behavioral switching. As a result the behavioral oscillations are eliminated and the robots overt behavior is smooth. For other applications in robotics using competitive dynamics see (Steinhage, 1998; Steinhage and Bergner, 1998; Large *et al.*, 1999; Schöner and Santos, 2001).

We report tests with a team of two mobile robots. Results in indoor environments show that if parameter values are chosen within reasonable ranges then, in spite of noise in the robots communication and sensors, the overall robotic system works quite well even in cluttered environments.

The rest of the paper is structured as follows: next section presents the robots and task constraints. In section 3 we describe the behavioral dynamics for each robot in the team. The competitive dynamics for behavioral switching is defined in section 4. Implementation details and results obtained from real experiments are presented in section 5. The paper ends with section 6 with conclusions and an outlook for future work.

2. TASK CONSTRAINTS AND ROBOT TEAM

The control and coordination of the two robots is based on the following ideas:

i) The *leader* robot holds an extremity of the object and moves from an initial position to a final target destination while avoiding sensed obstacles.

ii) The *follower* robot "helps" the *leader* to carry the long object from the initial position to the final destination. This implies that this robot has to steer so that it keeps at all times an appropriate orientation and distance to the *leader* (i.e. an adequate formation). By default the robots must transport the object side by side (i.e. line formation). However, due to the obstacles this might not be possible. When obstructions are sensed the *follower* must drive in "transition" and/or column formation. Once it is possible it must return to the line formation again (Figure 2).

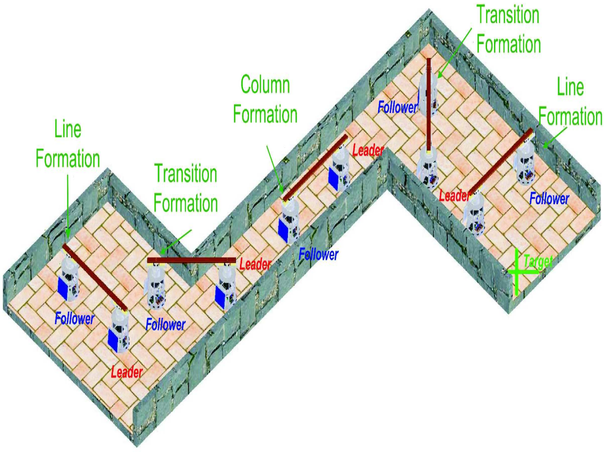

Fig. 2. By default the robots must transport the object keeping a line formation. When due to encountered obstacles that is not possible the *follower* robot must change its direction of navigation appropriately as illustrated.

iii) Each robot has a free rotational joint coupled to a free prismatic joint (see Figure 3). These are used to support the object and provide important information to the robot (see Figure 4): *a)* from the current angle of the free rotational joint the *follower* knows the direction, ψ_{leader}, at which the *leader* is as seen from its current position and with respect to the external reference axis x; *b)* displacements (Δd) of the object are measured in the free prismatic joint.

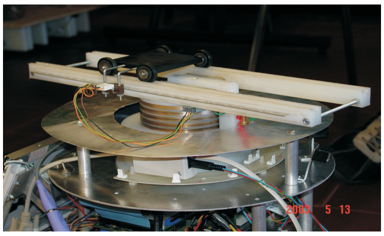

Fig. 3. We built a base for the object that consists of a 360 deg rotational free joint and a prismatic free joint coupled as illustrated here. The prismatic joint is an ensemble of a linear slider and moving cart, with 30 cm travel distance. The prismatic joint is connected to a linear incremental encoder which measures the distance of the cart to the reset position (i.e. Δd). To measure ψ_{leader}, the rotational joint integrates a rotational absolute position encoder.

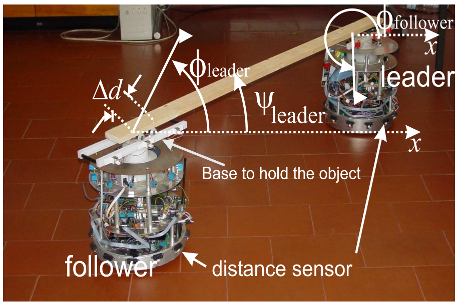

Fig. 4. The robots are tightly coupled through a rotary and a prismatic free joints as depicted. Each mobile robot consists of a cylindrical platform with two lateral motorized wheels and a passive rear caster wheel. Each platform has a single board computer system based on a 586DX4 processor operating at 133 MHz, equipped with 4 Mbytes of DRAM and 8 Mbytes of FLASH memory. All programming, control and computation are done on-board. The two lateral wheels are each driven by DC brushless servo-motor, each separately controlled by electronic circuitry that guarantees accurate control of rotation speed. Each robot is equipped with nine infra-red sensors, which are used to measure distance to obstructions at the directions at which they are pointing in space. Their signal is uncalibrated as it depends on surface reflectivity. The angular range over which distances are averaged is about 30 deg. They are mounted on a ring centered on the robot's axis. The sensors are arranged such that their sensitive cones just touch, thus completely covering the forward semi-circle. The distance range was set to 80 cm.

iv) The maximum allowed displacement of the object is ±15 cm (i.e. $\Delta d_{\max} = \pm 15$) otherwise the object falls down.

v) The *leader* sends to the *follower* only its current path velocity and heading direction. The *follower* sends to the *leader* the measured value Δd.

3. ATTRACTOR DYNAMICS FOR OBJECT TRANSPORTATION

To model the robots' behavior we use their *heading direction*, ϕ_r ($0 \leq \phi_r \leq 2\pi$ rad), with respect to an arbitrary but fixed world axis and *path velocity*, v_r. Behavior is generated by continuously providing values to these variables, which control the robot's wheels. The time course of each of these variables is obtained from solutions of dynamical systems. The attractor solutions (asymptotically stable states) dominate these solutions by design. In the present system, the *behavioral dynamics* of heading direction, $\phi_r(t)$, and path velocity, $v_r(t)$,($r = \text{leader}, \text{follower}$) are non-linear dynamical systems defined as differential equations

$$\dot{\phi}_r = f_r(\phi_r, \text{parameters}) \tag{1}$$

$$\dot{v}_r = g_r(v_r, \text{parameters}). \tag{2}$$

where the vector fields, $f_r(\phi_r, \text{parameters})$ and $g_r(v_r, \text{parameters})$, consist of a number of additive contributions that express task constraints or elementary behaviors.

The *leader*'s heading direction and path velocity dynamics has been previously defined and evaluated:

$$\dot{\phi}_{\text{leader}} = f_{\text{obs}}(\phi_{\text{leader}}) + f_{\text{tar}}(\phi_{\text{leader}}) + f_{\text{stoch}} \tag{3}$$

$$\dot{v}_{\text{leader}} = g_{\text{obs}}(v_{\text{leader}}) + g_{\text{tar}}(v_{\text{leader}}) \tag{4}$$

These vector fields have two components, indexed by obs and tar, that represent the obstacle and target contributions, respectively. The stochastic force guarantees escape from unstable fixed points in the heading direction dynamics (for details (Bicho *et al.*, 2000; Bicho, 2000)).
The complete behavioral dynamics of the *follower*'s heading direction and path velocity is also governed by a non-linear dynamical system which has been previously defined (see (Soares and Bicho, 2002; Soares *et al.*, 2007)):

$$\begin{aligned}\dot{\phi}_{\text{follower}} =& \mid S_{\text{line}} \mid f_{\text{line}}(\phi_{\text{follower}}) \\ &+ \mid S_{\text{tran}} \mid f_{\text{tran}}(\phi_{\text{follower}}) + \mid S_{\text{col}} \mid f_{\text{col}}(\phi_{\text{follower}}) \\ &+ f_{\text{stoch}}\end{aligned} \tag{5}$$

$$\begin{aligned}\dot{v}_{\text{follower}} =& \mid S_{\text{line}} \mid g_{\text{line}}(v_{\text{follower}}) \\ &+ \mid S_{\text{tran}} \mid g_{\text{tran}}(v_{\text{follower}}) + \mid S_{\text{col}} \mid g_{\text{col}}(v_{\text{follower}})\end{aligned} \tag{6}$$

where the indexes line, tran and col refer to the components of the vector fields that model the behaviors line, transition and column formations respectively. S_{line}, S_{tran} and S_{col} are mutually exclusive activation variables that, depending on the sensorial information acquired by the distance sensors mounted on the *follower* robot and the current heading direction of the *leader* robot (i.e. $\phi_{\text{leader}}(t)$), determine which component term of the vector field must dominate the dynamics. In our previous work these variables were implemented as a non-linear static model. This raised the problem of oscillations during behavioral switch. To overcame this drawback we make the activation variables dynamic as explained next.

4. COMPETITIVE DYNAMICS FOR BEHAVIOR COORDINATION

The control over activation and deactivation of the activation variables is obtained using a competitive dynamics (see e.g. (Schöner and Dose, 1992; Steinhage, 1998; Steinhage and Bergner, 1998; Schöner and Santos, 2001) for other applications):

$$\begin{aligned}\dot{S}_{\text{line}} &= \alpha_{\text{line}} S_{\text{line}} - |\alpha_{\text{line}}| S_{\text{line}}^3 - \\ &\quad S_{\text{line}}(\beta_{l,t} S_{\text{tran}}^2 + \beta_{l,c} S_{\text{col}}^2) + f_{\text{stoch}} \\ \dot{S}_{\text{tran}} &= \alpha_{\text{tran}} S_{\text{tran}} - |\alpha_{\text{tran}}| S_{\text{tran}}^3 - \\ &\quad S_{\text{tran}}(\beta_{t,l} S_{\text{line}}^2 + \beta_{t,c} S_{\text{col}}^2) + f_{\text{stoch}} \\ \dot{S}_{\text{col}} &= \alpha_{\text{col}} S_{\text{col}} - |\alpha_{\text{col}}| S_{\text{col}}^3 - \\ &\quad S_{\text{col}}(\beta_{c,t} S_{\text{tran}}^2 + \beta_{c,l} S_{\text{line}}^2) + f_{\text{stoch}}\end{aligned} \tag{7}$$

This dynamical system has $(S_{\text{line}}, S_{\text{tran}}, S_{\text{line}}) = \{(0,0,0), (\pm1,0,0), (0,\pm1,0), (0,0,\pm1)\}$ as fixed points. Their stability depends on parameters α_{i} (i=line, tran, col).

In the absence of sensed obstacles the terms f_{line} and g_{line} must dominate the vector fields in Eqs.5 and 6, respectively. Thus $(S_{\text{line}}, S_{\text{tran}}, S_{\text{line}}) = (\pm1,0,0)$ must be made asymptotically stable fixed points of the competitive dynamics. This can be achieved guaranteing that $\alpha_{\text{line}} > 0$, $\alpha_{\text{tran}} < 0$ and $\alpha_{\text{col}} < 0$ when obstacles are not sensed or their repulsion is weak.

Conversely, when obstructions are detected and the difference between the direction ψ_{leader} and ϕ_{leader} is larger than θ the robots must drive in transition formation, so the terms f_{tran} and g_{tran} must dominate the vector fields. This requires that states $(S_{\text{line}}, S_{\text{tran}}, S_{\text{col}}) = (0,\pm1,0)$ must be asymptotically stable fixed points. This happens when $\alpha_{\text{line}} < 0$, $\alpha_{\text{tran}} > 0$ and $\alpha_{\text{col}} < 0$.

Else, if obstructions are detected but the difference between the direction ψ_{leader} and ϕ_{leader} is smaller than θ we want the robots to move in column formation, thus the states $(S_{\text{line}}, S_{\text{tran}}, S_{\text{col}}) = (0,0,\pm1)$ must be now asymptotically stable fixed points of the competitive dynamics. Achieved by making $\alpha_{\text{line}} < 0$, $\alpha_{\text{tran}} < 0$ and $\alpha_{\text{col}} > 0$.

α_{line}, α_{tran} and α_{col} determine the relaxation rate to the states $(\pm1,0,0)$, $(0,\pm1,0)$ and $(0,0,\pm1)$. β_{ij} permits to control the inhibition of S_j over S_i (i,j=line, tran, col, and (i $\neq$ j)).

A function that indicates if obstacle contributions are present is the potential function of the obstacle avoidance dynamics for this robot, $U_{\text{obs}}(\phi_{\text{follower}})$, which has been defined in (Bicho and Schöner, 1997; Bicho *et al.*, 2000). Has shown, positive values of this potential function indicate that the robot's heading direction is in a repulsion zone of sufficient strength. Conversely, negative values of the potential indicate that the heading direction is outside the repulsion range or repulsion is very weak. Applying a sigmoidal threshold function,with a large slope, to the potential we get a function that ranges from -1 to 1:

$$\alpha_{\text{pot}}(\phi_{\text{follower}}) = 2\arctan[c_s\ U_{\text{obs}}(\phi_{\text{follower}})]/\pi \tag{8}$$

Also, applying a sigmoidal threshold function, with a large slope, to the difference $\mid \psi_{\text{leader}} - \phi_{\text{leader}} \mid -\theta$:

$$\alpha_{\Delta} = 2\arctan[c_s\ (\mid \psi_{\text{leader}} - \phi_{\text{leader}} \mid -\theta)]/\pi \tag{9}$$

we can write the following quasi-boolean functions (note that these are mutually exclusive) that indicate which behavior is the desired:

$$\gamma_{\text{line}} = 1 - \alpha_{\text{pot}}(1+\alpha_{\text{pot}})/2 \tag{10}$$

$$\gamma_{\text{tran}} = \alpha_{\text{pot}}(1+\alpha_{\text{pot}})(1+\alpha_{\Delta})/4 \tag{11}$$

$$\gamma_{\text{col}} = \alpha_{\text{pot}}(1+\alpha_{\text{pot}})(1-\alpha_{\Delta})/4 \tag{12}$$

We have realized, through experiments with the platforms, that the performance of the robotic system is improved when for the same sensory conditions the behavioral switch from *transition formation* or *column formation* to *line formation* occurs later in time and is slower then the reverse (i.e. $\alpha_{\text{line}} < \alpha_{\text{tran}}, \alpha_{\text{col}}$).

Finally, setting

$$\alpha_{\text{line}} = \alpha_1 \cdot (-1)^{(1-\gamma_{\text{line}})}\ , \alpha_1 > 0 \tag{13}$$

$$\alpha_{\text{tran}} = \alpha_2 \cdot (-1)^{(1-\gamma_{\text{tran}})}\ , \alpha_2 > 0 \tag{14}$$

$$\alpha_{\text{col}} = \alpha_3 \cdot (-1)^{(1-\gamma_{\text{col}})}\ , \alpha_3 > 0 \tag{15}$$

in the competitive dynamics guarantees that the adequate activation variable relaxes to ±1 (with a relaxation rate determined by α_i, i = line, tran, col) while the other two relax to 0.

5. IMPLEMENTATION AND RESULTS

The complete dynamic architectures, including the attractor dynamics for object transportation and the competitive dynamics for behavior coordination, were implemented and evaluated on the robots. In the implementation all differential equations are integrated numerically using the forward Euler method. Sensory information is acquired once per computation cycle. The cycle(step) time is measured and is approximately 50 ms for the *leader* and 60 ms for *follower*. As the time step must be smaller than the fastest relaxation time on the system, this imposes minimal time scales on the entire dynamical architectures. Thus the computational cycle time is the limiting factor for determining the relaxation times of the dynamics in real time units and thus for the overall speed at which the robots' behavior evolves. Because the systems operate close to attractors of known stability, the time scales, or reversely the relaxation rates in, can be set as a function of the computation cycle and thus guarantee the numerical stability. The rate of change of heading direction obtained from the dynamics of heading direction, i.e. Eqs. 3 and 5, directly specifies the angular velocity of the robots for rotation around their center. The path velocity (obtained from the numerical integration of Eqs. 4 and 6) specifies the average rotation speed of both wheels. Together, the rotation speeds of both wheels are computed and sent as set points to the velocity servos of the two motors.

We filmed the robotic system in task scenarios where the two robots transport a long object in cluttered indoor environments. As may be seen on the videos the robots' overt behavior is smooth. This is due to how the competitive dynamics permits sensorial and communicated information to affect in a graded fashion, and with hysteresis, behavioral switch.

Figure 5 illustrates, in one of the tests,the robots' behavior through a sequence of video images. Figure 6 shows the activation variables' time series. The situation is a scenario testing the ability to carry the object while simultaneously coping with situations where obstacle avoidance is in conflict with the robots' task. Initially, the robots are placed as indicated in Panel A. The *leader* always moves toward the target while avoiding collisions. The follower steers so as to avoid collisions and to help the *leader* carrying the object. The *follower* starts by steering so as to keep a line formation and steering on the left side of the *leader* (Panels A - B). When it senses the obstacle it turns right and steers so that it follows the *leader* and simultaneously avoids collisions with the obstacles, i.e. transition formation (Panels C - F). Then the *leader* enters into the narrow passage (Panel G). During the movement through this narrow passage the follower keeps a column formation with the *leader* (Panels G - J). Once it is possible (Panel K) the *follower* tries to drive again in line formation with the *leader* until the final target position is reached (Panels L - N).

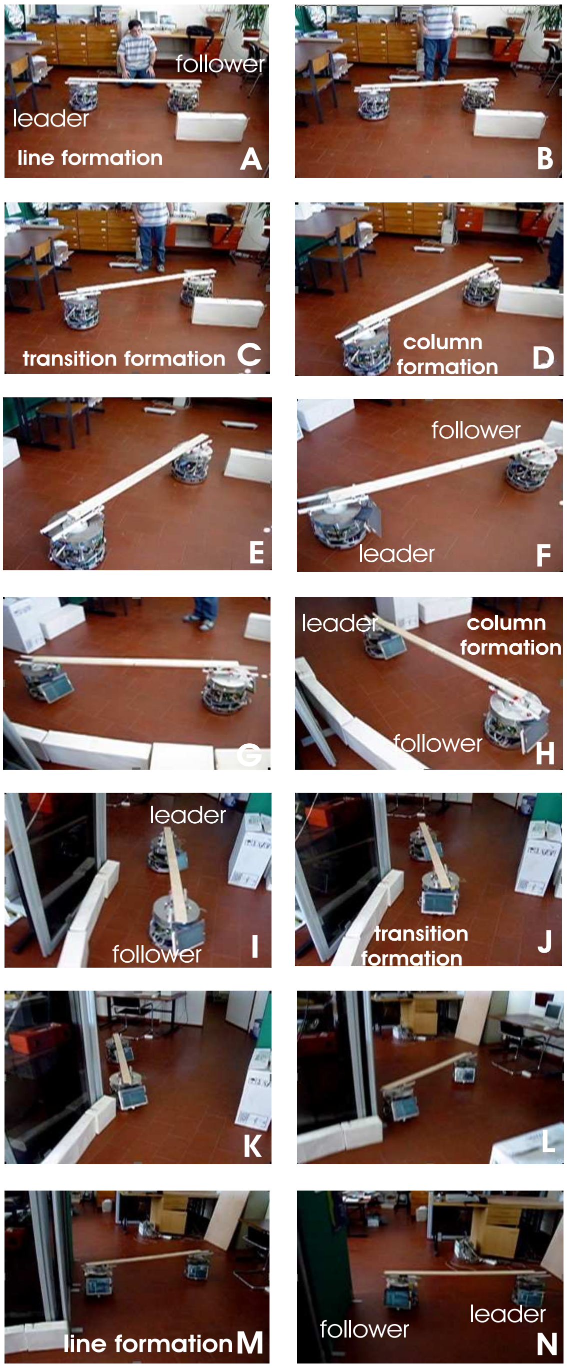

Fig. 5. Sequence of video images illustrates the motion of the robots while transporting an object in a cluttered environment. The robots move smoothly and around the obstacles.

6. CONCLUSION AND FUTURE WORK

We have shown how a competitive dynamics may be used to coordinate two non-holonomic mobile robots that move in formation while transporting a long payload in cluttered indoor environments. Results have demonstrated that robots' overt behavior is stable and smooth. Near future work is concerned with object transportation by teams of mobile manipulators and human-robot joint transportation.

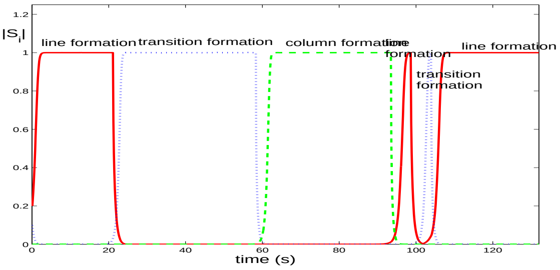

Fig. 6. Time series of $|S_{line}|$ (red full line), $|S_{\mathrm{tran}}|$ (blue doted line) and $|S_{\mathrm{col}}|$ (green dashed line). Active behavior is indicated. $\beta_{l,t} = 10$, $\beta_{l,c} = \beta_{t,l} = \beta_{t,c} = \beta_{c,t} = \beta_{c,l} = 0.8$ and $\alpha_1 = 3$, $\alpha_2 = \alpha_3 = 4$ and $\theta = 5deg$.

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