Object Transportation by a Human and a Mobile Manipulator: a dynamical systems approach

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***Abstract*—In this paper we address the problem of human-robot joint transportation of large payloads. The human brings to the task knowledge on the goal destination and global path planning. The robot has no prior knowledge of the environment and must autonomously help the human, while simultaneously avoiding static and/or dynamic obstacles that it encounters. For this purpose a dynamic control architecture, formalized as a coupled system of non-linear differential equations, is designed to control the behavior of the mobile manipulator in close loop with the acquired sensorial information. Verbal communication is integrated that allows the robot to communicate its limitations. Results show the robot's ability to generate stable, smooth and robust behavior in unstructured and dynamic environments. Furthermore, the robot is able to explain the difficulties it encounters and thus contribute to success of the task and to enhance the human-robot physical interaction.**

I. Introduction

Human-Robot cooperation is one of the key technologies to broaden the application field of robotics. By taking advantage of the strengths of both human and robot, more elaborated tasks, incapable of being performed by only one of the agents (robot or human) or even a team of robots, are now viable.

One of the problems addressed in Human-Robot cooperation concerns joint transportation of large objects [1], [2], [3]. In this task, the human may contribute by bringing intelligence and experience, global task knowledge, such as end goal and path planning, while the robot allows the execution of the task by autonomously helping the human to transport the object while avoiding static and/or dynamic obstacles that may appear in its navigation path.

The use of a mobile manipulator, instead of a simple mobile robot as in [2], allows a particular movement of the human partner to be followed by the robot by moving the manipulator, the mobile platform or a combined motion of both. Furthermore, the manipulator enables for a faster response of the robot to human movements, while at the same time allowing it to grasp and hold the object to be carried.

Despite the great potential of this Human-Robot cooperation for transportation tasks, the unknown and changing environment demands a complex dynamic behavior from the robot. Furthermore, this task also requires a close physical interaction with a human, thus the robot must exhibit a stable and smooth behavior that is influenced by the human's movements. On the other hand, the robot's movements may also influence the human partner. The so called Dynamics Approach to Behavior Generation [4] has been extensively and successfully implemented in mobile robot navigation [5], [6], multiple robots coordination for object transportation and formations [7], [8], mobile manipulator navigation [9], and Human-Mobile robot object transportation [2]. It is based on the mathematical theory of non-linear dynamics and provides a theoretical framework and tools that allow the design of control architectures that generate the behavior of the (cooperating) robots.

In this paper we aim to extend the work developed in [2], where the robot consisted of a mobile platform with a 2 DoF (rotational and prismatic passive joints) support on top of it and verbal communication was not considered, into the domain of Human-Mobile Manipulator cooperation, which must integrate non-verbal and verbal communication. The remainder of the paper is organized as follows. Section I-A provides a summary of the related work to control a robot in an object transportation task with a human. The mobile manipulator is described in section II, followed by a dynamical architecture for the control of the mobile manipulator in section III. In section IV we present some experiments, followed by the conclusions in section V.

A. Related Work

Passive robotics concepts were proposed in [10]. In [11], the authors extended it to accomplish a physical interaction between human and robot. Despite the continuous development [12] there are some scenarios were the necessary force to keep the object on track may have a certain direction and magnitude such that the passive robot does not have enough brake units to generate the desired force for supporting the human's motion.

In [13], the authors proposed a decentralized control algorithm to distributed robot helpers (DR Helpers). Each robot is controlled as if it has caster-like dynamics and interacts with the human through an intentional force/moment, that the human applies to the object. However, by using such approach, the human may not be able to precisely apply a moment to the human's grasping point of the object in order to adjust its orientation to keep it on track and avoid obstacles, [14]. To overcome this problem, in [14] it was suggested a system where each robot has a map information of the environment,

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thus, enabling it to generate a path on the known environment and move along with a path velocity based on the intentional force applied by the human. Despite the good performance, the applicability of such systems is very limited, since no changes are allowed to the environment or task, and dynamic obstacles could not be modeled.

Compliant motion has been addressed by several researchers [15], [16], [17] as an approach for robot-environment and human-robot interaction, where both the dynamic behavior and the position of the manipulator are controlled based on the concept of mechanical impedance [15]. By building on previous work [18], [17] propose a variable impedance control where the impedance characteristics were changed according to the speed of motion, and it was verified that the human was able to perform quick actions, with the same controller having a positioning action without oscillations.

The problem of side-slip in impedance control proposed in [17] was considered in [3], where a method that suppresses the side-slip of the object by assigning a virtual nonholonomic constraint at the robot hand is presented. This obliges the human to steer the manipulation as a cart or wheelbarrow.

In [19], the authors proposed an approach where no prior planning was assumed by the robot, and the human takes the lead while the mobile manipulator helps support the object and follows the human. They considered force control in the inertial z-axis direction to sustain the object while the manipulator is left free-floating inside the xy-plane. This way, the manipulator is dragged in the xy-plane by the friction force between the end effector and the object. They have used the manipulability measure of the manipulator as a criterion for optimal coordination of both platform and manipulator motions. However, the task may fail when the necessary force to drag the latter supersedes the friction force between the end-effector and the object.

A systematic derivation of the effort sharing policies was proposed in [1]. The authors considered three different policies where the effort (degree of assistance) is changed to tune the pro-activity of the robot. Besides the overall performance, a commonly known trajectory of the configuration was assumed.

Based on intention recognition, in [20] it was proposed an approach for active human-mobile manipulator cooperation, reducing the continuous human effort to maintain the movement, thus making transportation faster. Such is achieved by the search for spectral patterns in the force signal measured at the manipulator gripper. The system demonstrated satisfactory performance, nonetheless, it still needs an improvement in robustness [20] and robot's behavior does not integrate obstacles avoidance capabilities.

In active human-robot cooperation based on motion estimation [21], the position of the human hand is treated as the desired position of virtual compliance control. The human could manipulate the object as intended, however, the task was carried under limited movement of horizontal, one dimensional, transportation of the object.

A behavior-based approach was proposed in [2], where a dynamical control architecture, formalized as non-linear dynamical systems, controls the behavior of the autonomous mobile robot (without a manipulator) that must transport a large size object in cooperation with a human. In the proposed approach, the robot has no prior knowledge of the environment and the navigation is based on information of target orientation relative to the robot's heading direction, and obstacles orientation and distance. To note that, in the work reported in [2] verbal communication was not considered, which as we show here may enhance the physical interaction between human and robot. As the sensed world changes, the robot's behavior is adjusted accordingly. It was shown that the system is robust against perturbations, stable and the trajectories are smooth, while the robot helps the human to carry a long object in an unstructured indoor environment.

In this paper we extend that work in two ways: *i)* a mobile manipulator is used, for which a dynamic control architecture is developed; *ii)* verbal communication is integrated, that allows the robot to communicate its own difficulties, thus enhancing the execution of the task.

II. The Mobile Manipulator: Dumbo

A. Hardware

Dumbo robot is comprised of a differential mobile platform with a robotics arm coupled. The mobile platform makes use of 2 DOF for steering along with path velocity for translation, while the manipulator has 7 DOF (*amtec™lwa 7dof*) and its end-effector is a 1 DOF gripper. It features a laser range finder, URG-04LX, a 6 axis force/moment sensor between the end-effector and the arm, a speaker and a digital compass. All the hardware modules are connected to a computer, which supports all computational requirements. It is a Centrino M 1.7 GHz CPU, with 2 GB of RAM and 40 GB of hard disk drive. To suppress all connection requirements, a 4 port RS232 - PCI expansion card and a USB hub was added. Despite only having one computer, an Ethernet switch and wireless access point were added to allow connections from remote computers to debug and to monitor the task, while experiments are being performed.

B. Software

The on-board computer runs the Windows® Embedded Standard 7 operating system which has a network of modules, with an inter-process communication mechanism based on YARP [22], that manages the *sensorimotor* system. The software architecture is divided in: 1) a set of devices that comprise the Hardware Abstraction Layer and communicate directly with the hardware modules; 2) control application, which performs all the calculus required by the dynamical architecture, presented in section III, and connects to the devices to acquire sensory information and command the motors; 3) auxiliary software to monitor the task, such as the Matlab_Viewer, which is a GUI application developed under MATLAB® and allows the remote visualization and debug of the robot's internal dynamics.

III. DYNAMICAL ARCHITECTURE

A human operator and an autonomous mobile manipulator must, together, transport a long object in an unstructured and unknown environment. A *human-follower* motion control strategy is adopted where the human assumes the leadership of the task, since he/she knows the end goal of the task. The robot must be able to help him/her, for smooth and safe execution of the task, while avoiding static and/or dynamic obstacles that it may encounter.

As a first approach, the manipulator movements were not considered since these require inverse differential kinematics, which is very complex in redundant manipulators, like this one, and involves avoidance of singularities, whose calculations mean high computational costs. This implies that some flexibility is lost, however the benefit is that the control solution becomes simplified, easy to implement and fast to compute. A (sub)optimal posture was adopted which: 1) avoids joints limits and singularities; 2) places the end-effector at the height of the human partner and 3) allows free rotation on its wrist, parallel to ground. In this task, the grasping is non-compliant and it is assumed that the robot is already holding the object before the transportation starts and it is not unloaded at finish time. Such subtasks include: (a) the search for the object, e.g. with the vision system, (b) platform movement towards object location and (c) final grasping and lifting up maneuvers, using the manipulator.

The robot uses the direction to where the object is moving (read directly from the rotational joint on the wrist, $\Psi_{tar,R}$) and moment information from the force/moment sensor as non-verbal communication. Obstacles are sensed by the laser range finder. This information ($\Psi_{tar,R}$ and force/moment) is easily gathered with the adopted manipulator configuration. Nevertheless, it may also be acquired recurring to manipulator kinematics transformations if the manipulator is moving. Comparing Fig. 1 with Fig. 2 we can see that $\Psi_{tar,R}$ may be replaced by θ.

The platform's navigation is expressed in terms of angular velocity, $w = d\phi/dt$, and path velocity, v, [4]. Behavioral constraints are defined by directions of moving target or obstacles relative to a fixed world reference frame and restrictions on path velocity.

A. The dynamics of heading direction

1) Target acquisition: The target acquisition behavior is specified in the vector-field erecting an attractor (asymptotically stable state) at the orientation Ψ_{tar} (target direction, human, relative to a fixed world reference frame, see Fig. 1), and a repeller (unstable state) at the opposite direction, with strength λ_{tar}. Regardless of current heading direction, it is desired that the robot orientates itself towards this direction. Thus, this contribution should exhibit an attractive force over the entire range of heading direction. The mathematical form reads:

$$\frac{d\phi}{dt} = f_{tar}(\phi) = -\lambda_{tar}\sin(\phi - \Psi_{tar}) \qquad (1)$$

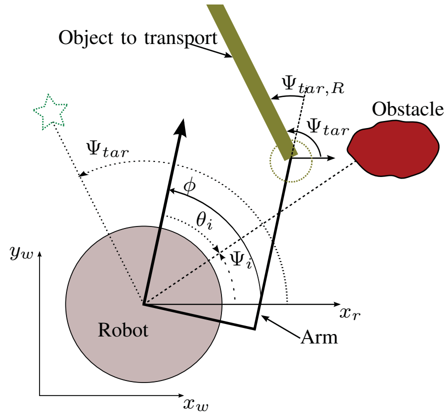

Fig. 1. Target acquisition and obstacle avoidance task constraints. Ψ_i is the direction at which the obstacle lies (the direction to be avoided) from the current position of robot. Ψ_{tar} is the desired (target) direction for the robot and it is the same in robot's center since the reference axis are kept parallel. The direction of x_r axis is kept parallel to a x_w during the robot's movements. This means that if the robot rotates about itself, the x_r axis will be parallel to x_w and so Ψ_i and Ψ_{tar} will be constant. If robot moves with translational velocity, x_r will move with it, but parallel to x_w, and Ψ_i and Ψ_{tar} will change accordingly.

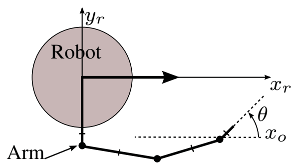

Fig. 2. With different arm configurations, θ is the angle in xy plane between x_o and end-effector direction, where $x_o // x_r$.

The current robot's heading direction ϕ is referenced to a fixed world reference frame, and $\Psi_{tar} = \phi + \Psi_{tar,R}$, thus, we have

$$\phi - \Psi_{tar} = \phi - (\phi + \Psi_{tar,R}) = -\Psi_{tar,R} \qquad (2)$$

where $\Psi_{tar,R}$ is acquired directly from the encoder of the free rotational joint on the robot wrist. Since ϕ cancels out, target orientation does not need to be known relative to an external fixed world frame of reference and it is not influenced by calibration errors of the digital compass. This implies that (1) can be rewritten as

$$\frac{d\phi}{dt} = f_{tar}(\phi) = \lambda_{tar}\sin(\Psi_{tar,R}) \qquad (3)$$

2) Obstacle avoidance: The obstacle avoidance behavior is expected to steer the robot away from obstacles that lie in its navigation path. Dumbo robot is equipped with a laser range finder, whose range was split in sectors. Each sector gets a fixed direction, θ_i (see Fig. 1), relative to the robot's heading direction and a $\Psi_i = \phi + \theta_i$ relative to the world reference axis. i denotes the number of the sector, ranging from $i = 1 \ldots n$, where n represents the number of sectors. For each sector, the dynamics should erect a repeller at the direction Ψ_i:

$$\begin{aligned} f_{obs,i} &= \lambda_{obs,i}(\phi - \Psi_i)\exp\left[-\frac{(\phi-\Psi_i)^2}{2\sigma_i^2}\right], i = 1 \ldots n \\ &= -\lambda_{obs,i} \times \theta_i \times \exp\left[-\frac{\theta_i^2}{2\sigma_i^2}\right] \quad , i = 1 \ldots n \end{aligned} \qquad (4)$$

As in (1) for target acquisition behavior, here, also, only the relative orientation θ_i of each sector i to robot's heading direction ϕ appears in the dynamics of heading direction. Thus the obstacle avoidance behavior is also not affected by calibration errors. In (4), $\lambda_{obs,i}$ is the strength of repulsion at direction Ψ_i and σ_i is the range of such repulsion. The mathematical form for these two parameters can be found in [4]. The final obstacle avoidance dynamics is obtained from the sum of the contribution of each sector $i = 1 \ldots n$:

$$\frac{d\phi}{dt} = F_{obs}(\phi) = \sum_{i=1}^{n} f_{obs,i}(\phi) = -\sum_{i=1}^{n} \lambda_{obs,i}\theta_i \exp\left[-\frac{\theta_i^2}{2\sigma_i^2}\right] \tag{5}$$

3) Integrating the two behaviors: The robot's behavior results from the following dynamical system, that integrates the two task constraints, follow the human and avoid collisions:

$$\begin{aligned} \tfrac{d\phi}{dt} = f_{robot}(\phi) &= -\lambda_{tar}\sin(\phi - \Psi_{tar,obs}) \\ &= \lambda_{tar}\sin(\Psi_{tar,R} + \Psi_{turn}) \end{aligned} \tag{6}$$

where $\Psi_{tar,obs}$ is the desired direction for the robot, given by:

$$\Psi_{tar,obs} = \Psi_{tar} + \Psi_{turn} \tag{7}$$

The angular value Ψ_{turn} is a function of obstacles contribution and results from a sigmoid function that rises smoothly from an inferior limit, $\dot{\phi}_i$, to a superior limit, $\dot{\phi}_s$, between a symmetric threshold value, ϕ_t:

$$\Psi_{turn} = \begin{cases} -\phi_t & \text{if} \quad F_{obs}(\phi) \le \dot{\phi}_i \\ -\phi_t \cos\left(\pi \frac{F_{obs}(\phi) - \dot{\phi}_i}{\dot{\phi}_s - \dot{\phi}_i}\right) & \text{if} \, \dot{\phi}_i < F_{obs}(\phi) < \dot{\phi}_s \\ \phi_t & \text{if} \quad F_{obs}(\phi) \ge \dot{\phi}_s \end{cases} \tag{8}$$

$\dot{\phi}_i$, $\dot{\phi}_s$ and ϕ_t are design parameters.

The sigmoid function and the integration of obstacles contribution in target dynamics allows the control to take into account the target direction even in presence of obstacles, see Fig. 3. If a simpler integration of the two behaviors, such as in [4], would be used, when obstacles are near the robot, very strong repellers would be erected and the target contribution would be easily superseded by obstacles contribution, leading the robot to avoid the obstacles without taking into account the human direction in its behavior, dashed blue line in Fig. 3.

B. The dynamics of path velocity

To completely define the time courses of the robot behavioral variables, a dynamical system for path velocity should be specified. Every dynamic change in the sensed environment (because the robot moves or the environment changes over time) leads to a shift in attractors and repellers. Despite these shifts, the system must remain stable to guarantee the asymptotically stability of the overall control system. We must make sure that the control variables track one of the attractors as they move. In other words, the robot's heading direction should be in or near an attractor at all times [4]. Such task may be accomplished by controlling the path velocity, v, of the mobile platform:

$$\frac{dv}{dt} = g(v) = -c_{obs}(v - v_{obs}) - c_{tar}(v - v_{tar}) \tag{9}$$

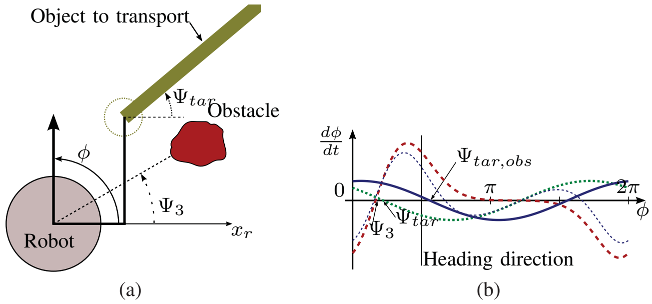

Fig. 3. Integration of Target and Obstacles behaviors. The sum of obstacles contributions, dashed red line, erects two different repulsive force-lets. Target acquisition dynamics contribution is represented by the dotted green line. The resultant non-linear dynamical system, solid blue line, has the same shape as target acquisition, but the attractor is shifted by the obstacles contribution.

The desired path velocity is controlled such that the presence of obstacles influences the velocity contribution of the target. c_i ($i = tar$ or obs) indicates the strength of each contribution [4]. When the potential function ($U(\phi)$), as explained in [4], is negative, no obstacles were detected, or the robot's heading direction is outside the repulsion zone. The robot must then navigate with a velocity, v_{tar}, proportional to the force/moment sensor readings. A positive value of $U(\phi)$ implies that the robot's heading direction is in a repulsion zone, and the robot must take into account the presence of obstacles. The path velocity, v_{obs}, is then controlled by the minimum between the velocity to follow the human (proportional to force/moment readings) and a velocity function of the distance to obstacles:

$$v_{obs} = \min(d_{min}/T_{2c,obs}, v_{tar}) \tag{10}$$

where d_{min} is the distance to the nearest obstacle and $T_{2c,obs}$ is a parameter defining the time to contact with the obstacle. The velocity dynamics presented in (9) guarantees smooth transitions between the velocities.

C. Speech

In order to ease task execution, the robot must communicate its own limitations, which may consist of physical or environment constraints. If the human enters a passage too narrow for a safe navigation of the robot, the previous dynamical architecture will not allow the robot to keep the movement, resulting in a dead end. A set of conditions, to the resultant of the dynamical systems, is applied, in order to address this situation, and others alike. This way, a narrow passage may be detected by, see Fig. 4:

$$narrow\_passage = \text{abs}(\alpha(\phi)) > 0 \wedge \text{abs}(\dot{\phi}) < \dot{\phi}_{min} \tag{11}$$

where $\alpha(\phi)$ is a sigmoidal threshold function, see [4], $\dot{\phi}$ is the current robot angular velocity and $\dot{\phi}_{min}$ is a design parameter. The instant that these conditions are verified, the robot synthesizes *"Wait! This passage is too narrow for me!"*. Similarly, detecting that the human is moving too fast and that the robot can not follow him is signaled by:

$$too\_fast = \text{abs}(v_{force} - v) > \Delta v_{max} \tag{12}$$

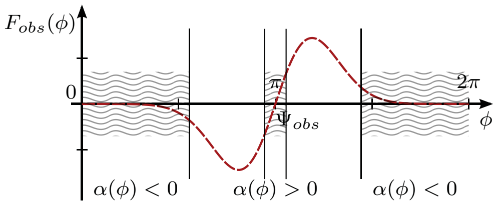

Fig. 4. In a narrow corridor, the resulting obstacles contribution has the shape presented above where, in the shaded areas, the rate of change of heading direction is too low, thus the robot moves slowly.

where $v_{force} = v_{tar}$ is the velocity attractor (when no obstacles are present) of the path velocity dynamics, which is proportional to the force applied by the human to the robot's end-effector. v is the current path velocity and Δv_{max} is a design parameter. When the distance between the desired velocity and actual velocity is higher than Δv_{max} threshold value, the sentence *"Wait! Go slower! I can not move so fast!"* is synthesized by the robot.

IV. Results and Discussion

The complete dynamical architecture was tested on the Dumbo robot in an Entrance Hall scenario. Static and dynamic obstacles are in the robot's navigation path and no predefined trajectory is given. In the implementation, the result of the heading direction dynamical system, $\dot{\phi} = w$ (6), is sent directly to the motors, while the result from the path velocity dynamical system, $\dot{v}$ (9), is integrated numerically using the forward Euler method. Fig. 5 shows a sequence of snapshots obtained from a video that can be downloaded from our MARL web server[1].

From 0s to 14s, the human performs a movement in a straight line leading the robot to follow him. At instant t=14s (Figure 5a), the human goes through a passage that is large enough for him but too narrow for the robot. The sensed obstacles lead to a decrease in the robot's speed, which is characterized by a value of 0.5 in the sigmoidal threshold function (magenta solid line in Figure 5b) at the robot's heading direction (solid vertical line). Thus, the desired robot's path velocity is the minimum between the velocity to follow the human and a velocity function of the distance to the obstacles, see (10). As the human continues his movement, the robot approaches the obstacles and detects, at instant t=24s, that the passage between these obstacles is too narrow for a safe movement, verbally alerting the human. The human acknowledges the robot's difficulty and starts to pursue another pathway. From instant t=24s (Fig. 5c) to t=50s (Fig. 5i), the human changes his navigation path, shifting the attractor along with it. Around instant t=48s, an object was thrown to the robot's path, with the resultant direction to be avoided (repeller) shifting along with the obstacle's movement. When the obstacle is near the current heading direction of the robot, path velocity is now governed by the distance to this obstacle.

[1] http://marl.dei.uminho.pt/Public/Robotica2012_Human-Robot_ObjTransp/

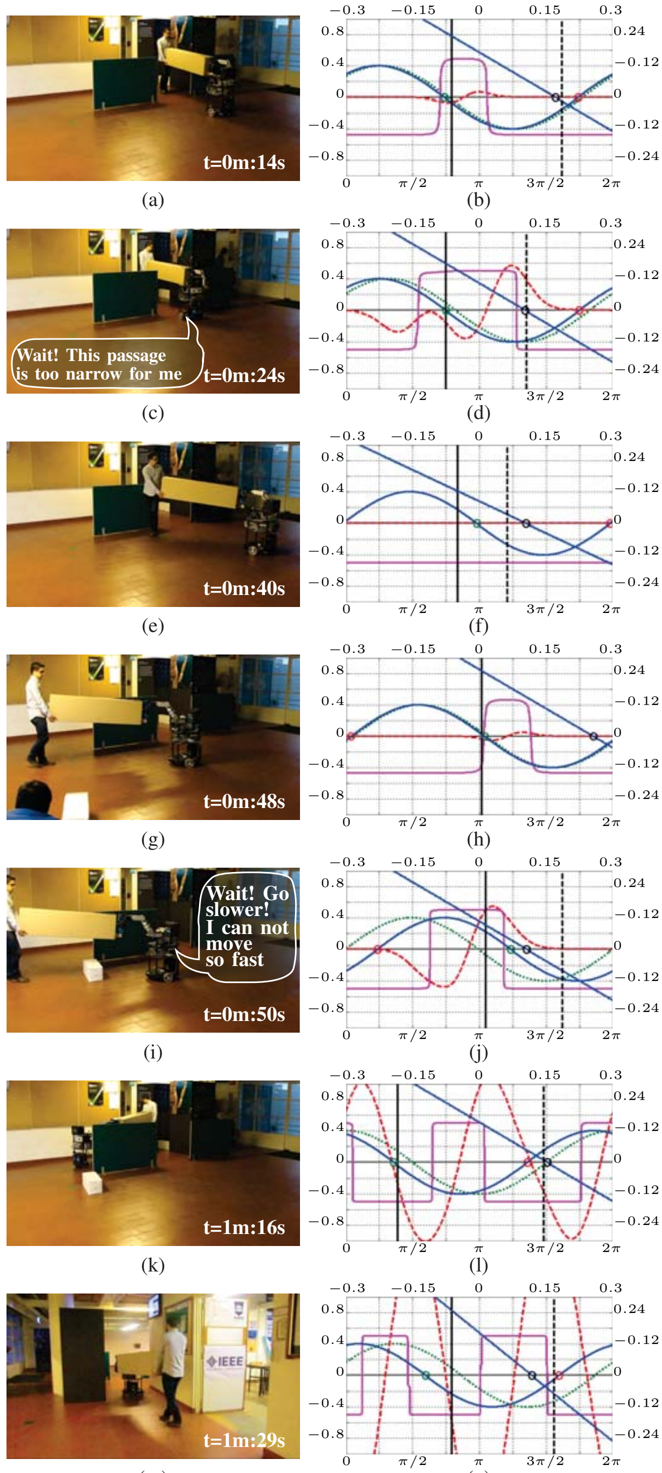

Fig. 5. On the right side are presented both heading direction and path velocity dynamics for the same instant. Left and lower axis are relative to heading direction, $d\phi/dt$ and ϕ, respectively. Right and upper axis are relative to path velocity dynamics, dv/dt and v, respectively. Vertical solid and dashed lines are heading direction and path velocity current values, respectively. Sinusoidal dotted green curve is the target acquisition contribution. Red dashed curve is the obstacles contribution and solid blue sinusoidal curve is the resultant behavior. Solid linear blue line is the path velocity dynamics. Solid magenta curve is the sigmoidal threshold function, see [4]. ϕ units is in radians, while v is m/s. Attractors and reppelers are represented by circles.

Since the human and the mobile manipulator were moving with a relatively high velocity, the robot can not continue to navigate with such velocity, alerting the human partner to the situation. The human acknowledges this instruction, reducing the exerted strength, and allowing the robot to safely avoid the obstacle, see Fig. 5i. As the human continues his movement, the target acquisition dynamics tries to align the robot's direction heading with the human and the obstacles avoidance dynamics tries to steer the robot through the passage, without colliding with the near by walls. As can be seen in instant t=1:16m, two strong repellers are erected at approximately $-\pi/2$ and $\pi/2$ from current heading direction (representing the contribution of both walls). Since the contribution of each wall is nearly the same, a resultant attractor is erected at the direction that keeps the robot equally spaced from both walls. The task ends with the human entering the room, Fig. 5m.

V. Conclusion

In this paper we have presented a dynamical control architecture that endows an autonomous mobile manipulator with the capability to help a human in a joint transportation task in dynamic environments. The robot's overall behavior is smooth and stable, where the information is locally gathered by the robot. The integration of speech synthesis, which allowed the robot to communicate its own difficulties, enhanced the execution of the task.

The issue of controlling simultaneously the movement of the robotic arm and mobile platform will be addressed in the very near future. It must be stressed out the need for the human to continuously exert strength to keep the robot in motion. An important next step will be to endow the robot with speech recognition, which may further enhance human experience and allow the inclusion of an adaptation/learning mechanism, enabling the robot to tune its internal design parameters on behalf of user's feedback.

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