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Adaptive unified motion control of mobile manipulators

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ABSTRACT

This paper presents a unified motion controller for mobile manipulators which not only solves the problems of point stabilization and trajectory tracking but also the path following problem. The control problem is solved based on the kinematic model of the robot. Then, a dynamic compensation is considered based on a dynamic model with inputs being the reference velocities to the mobile platform and the manipulator joints. An adaptive controller for on-line updating the robot dynamics is also proposed. Stability and robustness of the complete control system are proved through the Lyapunov method. The performance of the proposed controller is shown through real experiments.

1. Introduction

Mobile manipulator is nowadays a widespread term that refers to robots built with a robotic arm mounted on a mobile platform. This kind of system, which is usually characterized by a high degree of redundancy, combines the manipulability of a fixed-base manipulator with the mobility of a wheeled platform. Such systems allow the most usual missions of robotic systems which require both *locomotion* and *manipulation* abilities. They are useful in multiple applications in different industrial and productive fields, such as mining, construction, rescue missions or for people assistance (Das, Russell, Kircanski, & Goldenberg, 1999; Khatib, 1999). In recent years, much effort has been done to develop strategies for solving the motion problem of mobile manipulators. In most cases, the proposed controllers focus on only one of the motion problems: point stabilization (Gilioli & Melchiorri, 2002; Tsakiris, Kapellos, Samson, Rives, & Borrelly, 1997), path following (Chuyan, Zhang, & Sun, 2006; Egerstedt & Hu, 2000; Mazur & Szakiel, 2009), or trajectory tracking (Chi-wu & Ke-fei, 2009; Dong, 2002; White & Bhatt, 2009; Xu, Zhao, Yi, & Tan, 2009). At the very least, the proposed controllers address two motion problems (Monastero & Fiorini, 2009), but to the best of our knowledge, no control schemes have been reported to solve all the three above mentioned motion objectives. The control schemes can be classified into two categories. The first one is based on a decentralized control law, which uses a controller for the mobile platform and another one for the manipulator arm. The second category employs a single control law for the entire mobile manipulator system.

Regarding the point stabilization problem (Tsakiris et al., 1997) proposed a visual servoing technique to address the point stabilization problem. The proposal uses only the visual information provided by a camera mounted on the end-effector of the robotic arm. Another visual servoing technique is proposed in Gilioli and Melchiorri (2002) for solving the point stabilization problem. Here, the arm's joint displacements information is combined with the visual information in a hybrid control strategy. On the other hand, White and Bhatt (2009) solve the trajectory tracking problem including obstacles, by using an algorithm with two reference torque signals, one for the mobile platform and another for the end-effector of the manipulating arm. Results are illustrated with real experiments. Ge, Ye, Jiang, and Sun (2008) use a sliding mode control to solve the tracking trajectory problem for a mobile manipulator with a four-wheeled mobile platform. Authors propose a control system decomposed into two subsystems: a sliding mode control for the mobile platform and a non-singular terminal sliding mode control for the manipulator. Xu et al. (2009) propose a neural network-based sliding mode controller, which uses a neural network to identify the unstructured system dynamics. The controller is applied to an omnidirectional wheeled mobile manipulator.

As regarding the path following problem, the work in Egerstedt and Hu (2000) presents a platform independent control for mobile manipulation, and a coordinated trajectory following is proposed and analysed. Given a path for the gripper to follow, the idea is to plan another path for the mobile base. The proposed controller is validated by simulation. Chuyan et al. (2006) presents a controller based on a neural-network for dynamic

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compensation and coordinated control of the mobile manipulator. Recently, Mazur and Szakiel (2009) addressed the path following problem for two types of nonholonomic mobile manipulators. A cascade structure of two controllers is proposed to achieve the motion along the desired path while preserving an appropriate coordination between the mobile platform and the robotic arm.

To reduce performance degradation, on-line parameter adaptation is relevant in applications where the mobile manipulator dynamic parameters may vary, such as load transportation. It is also useful when the knowledge of the dynamic parameters is limited. Some of the most relevant works addressing the motion adaptive control problem of mobile manipulators are now commented. Phuong, Duy, Jeong, Kim, and Kim (2007) presents an adaptive tracking control method for a welding mobile manipulator with a kinematic model in which several dimensional parameters are unknown. The design of the controller is based on the Lyapunov method. Wu, Feng, and Hu (2005) presents the output tracking control problem of a general mobile manipulator, including motor dynamics with uncertain parameters in the generalized coordinate space. A dynamical adaptive sliding mode controller is designed. Liu and Li (2005) presents a sliding mode adaptive neural-network controller for trajectory following of non-holonomic mobile modular manipulators in the task space. Multilayered perceptrons (MLP) are used as estimators to approach the dynamic model of the mobile modular manipulator. Sliding mode control and a direct adaptive technique are combined to suppress bounded disturbances and modelling errors caused by parameter uncertainties. A torque compensation control is proposed for the motion control of a mobile manipulator in Chi-wu and Ke-fei (2009). By considering the modelling uncertainty and existing uncertainties disturbances, compensation is adopted for the proposed control law. Compensation is designed using the Lyapunov method. The design is validated using simulation.

In this paper, a robotic arm mounted on a non-holonomic mobile platform is considered. To solve the problems of point stabilization, trajectory tracking and path following for the mobile manipulator within a unified structure, a robust adaptive controller based on the mobile manipulator dynamics is presented. The controller design is based on a dynamic model of the mobile manipulator which accepts velocity inputs, as it is usual in commercial robots. The controller also maximizes the manipulability (Bayle & Fourquet, 2001) and provides the robot with the capability to avoid obstacles on its path. The controller design is based on two parts, each one being a controller itself. The first one is a minimum norm kinematic controller with saturation of velocity commands, which is based on the mobile manipulator's kinematics; and the second one is an adaptive dynamic compensation controller in which inputs are the velocities calculated by the kinematic controller. The adaptive dynamic compensation controller updates the estimated parameters, which are directly related to the physical parameters of the mobile manipulator. It is worth noting that in this work a single reference for the end-effector is determined, thus treating the mobile manipulator as a single coordinated system. Additionally, both stability and robustness properties to parametric uncertainties in the dynamic model are proved through Lyapunov's method. To validate the proposed control algorithms, experimental results are included and discussed.

The main contribution of this paper is the proposal of a unified controller for point stabilization, trajectory tracking and path following control of mobile manipulators. The unified controller, differently from the ones available in the references, has the advantage of solving any of the motion problems only by an adequate definition of references. The controller receives a single reference for the end-effector of the robot, and calculates the control commands as velocity references for both the platform and the arm achieving a coordinated movement of the whole system. The controller is complete, in the sense of including kinematic main and secondary motion control objectives, as well as an adaptive parameter compensation.

The paper is organized as follows: in Section 2 the kinematic and dynamic models featuring the manipulator velocities as inputs are obtained. The problem formulations both for trajectory tracking and path following are presented in Section 3. Section 4 presents the design of the kinematic controller and the adaptive dynamic compensation controller, including the stability and robustness analyses. The experimental results are presented and discussed in Section 5. Finally, conclusions are given in Section 6.

2. Mobile manipulators models

In this section, both the kinematic and the dynamic models of the mobile manipulator are presented. These two models are constructed by considering both the mobile platform and the robotic arm as parts of a unique system, according to the proposed control strategy. For this purpose, the mobile manipulator configuration is defined by a vector $\mathbf{q}=[q_1 \quad q_2 \quad \cdots \quad q_n]^T=[q_p^T \quad q_a^T]^T$ of n independent coordinates, called *generalized coordinates of the mobile manipulator*, where q_a represents the generalized coordinates of the arm, and q_p the generalized coordinates of the mobile platform. Notice that $n=n_p+n_a$, where n_a and n_p are, respectively, the dimensions of the generalized spaces associated to the robotic arm and to the mobile platform. The configuration $\mathbf{q}$ is an element of the mobile manipulator *configuration space*, denoted by $\mathcal{N}$. The location of the end-effector of the mobile manipulator is given by the m-dimensional vector of operational coordinates $\mathbf{h}=[h_1 \quad h_2 \quad \cdots \quad h_m]^T=[\mathbf{h}_{pos}^T \quad \mathbf{h}_{or}^T]^T$, where $\mathbf{h}_{pos}$ and $\mathbf{h}_{or}$ define the position and the orientation, respectively, of the end-effector in the operational space, denoted by $\mathcal{N}$. The location of the mobile manipulator end-effector can be defined in different ways according to the task, i.e., only the position of the end-effector or both its position and its orientation can be considered.

2.1. Mobile manipulator kinematic model

The *kinematic model of a mobile manipulator* gives the location of the end-effector $\mathbf{h}$ as a function of the robotic arm configuration and the platform location (or its operational coordinates as functions of the robotic arm's generalized coordinates and the mobile platform's operational coordinates) (Bayle, Fourquet, & Renaud, 2003)

$$f:\mathcal{N}_a \times \mathcal{M}_p \rightarrow \mathcal{M}$$
$$(\mathbf{q}_p,\mathbf{q}_a) \mapsto \mathbf{h}=f(\mathbf{q}_p,\mathbf{q}_a)$$

where $\mathcal{N}_a$ is the *configuration space* of the robotic arm, $\mathcal{M}_p$ is the *operational space of the platform*.

The *instantaneous kinematic model of a mobile manipulator* gives the derivative of its end-effector location as a function of the derivatives of both the robotic arm configuration and the location of the mobile platform

$$\dot{\mathbf{h}}(t)=\mathbf{J}(\mathbf{q})\mathbf{v}(t) \tag{1}$$

where $\dot{\mathbf{h}}=[\dot{h}_1 \quad \dot{h}_2 \quad \cdots \quad \dot{h}_m]^T$ is the vector of the end-effector velocity, $\mathbf{v}=[\nu_1 \quad \nu_2 \quad \cdots \quad \nu_{\delta_n}]^T=[\nu_p^T \quad \nu_a^T]^T$ is the vector of mobile manipulator velocities in which ν_p contains the linear and angular velocities of the mobile platform and ν_a contains the joint velocities of the robotic arm. The dimension of vector $\mathbf{v}$ is