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Linked multi-component mobile robots: Modeling, simulation and control

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ABSTRACT

The Linked Multi-Component Robotic Systems (L-MCRS) consists of a group of mobile robots carrying a passive uni-dimensional object (a hose or a wire). It is a recently identified unexplored and unexploited category of multi-robot systems. In this paper we report the first effort on the modeling, control and visual servoing of L-MCRS. Modeling has been tackled from geometrical and dynamical points of view. The passive element is modeled by splines, and the dynamical modeling is achieved by the appropriate extension of Geometrically Exact Dynamic Splines (GEDS). The system's modeling allows realistic simulation, which can be used as a test bed for the evaluation of control strategies. In this paper we evaluate two such control strategies: a baseline global controller, and a fuzzy local controller based on the observation of the hose segment between two robots. Finally, we have performed physical experiments on a team of robots carrying a wire under a visual servoing scheme that provides the perceptual information about the hose for the fuzzy local controller. Visual servoing robust image segmentation is grounded in the Dichromatic Reflection Model (DRM).

1. Introduction and motivation

Multi-component robotic systems (MCRS), or multi-robot systems, have been proposed in several application domains as a way to either perform a task that cannot be done by a single robot, or improve the efficiency (time or cost) of its realization even if it can be done by a single robot. Collaborative perception, morphological self-organization to overcome obstacles [1] or to establish communication links, are among the tasks performed by MCRS. In general, outside the industrial deterministic realm, MCRS have been proposed as a way to overcome the difficulties imposed by unstructured and non-stationary environments. There are several review works in the literature giving different categorizations of MCRS [2–6] focusing on different aspects of the multi-robot systems (communication topology, cooperation, geometrical restriction, learning mechanisms and others). A categorization of MCRS in terms of the degree of physical coupling among the individual robots is presented in [6]. That paper contains a discussion of several aspects of MCRS: their morphology, the tasks they have to perform and the environment in which they have to be carried out, the control of the system and the perception used to obtain feedback from the actions taken and their effects. However, for our purposes the main relevant idea of [6] is the identification of three main types of MCRS according to the individual's coupling degree:

- The Distributed MCRS (D-MCRS) which corresponds to groups of (mobile) robots without physical connection. Typical tasks for this kind of systems are collaborative perception and mapping of an environment, cooperative transportation of collections of items, etc.
- The Modular MCRS (M-MCRS) which corresponds to groups of modular robotic elements attached with rigid (strong, fixed) links to assume a given morphology which can be task-dependent. Typical tasks are self-organization for obstacle avoidance and environment adaptation, cooperative transportation of large rigid items.
- The Linked MCRS (L-MCSRS) which corresponds to groups of autonomous (mobile) robots linked through a passive non-rigid linking element. This passive element introduces dynamic problems and restrictions that may greatly influence the control of the whole robot ensemble. A typical task would be the manipulation and transportation of a hose or wire.

Both D-MCRS and M-MCRS have been dealt with extensively in the literature, however we find that the L-MCRS is a new category, not previously identified in the literature. To illustrate this point, let us consider the task of self-perception, the ability to measure the configuration of the system. The M-MCRS may sense its configuration through the state of its rigid joints connecting modules. The D-MCRS may estimate it from the information gathered by the individual robots independently. The L-MCRS, however, needs to perform both the estimation of the individual robot states and the state of the passive linking element. While the individual robot states can be estimated directly through odometry, the passive linking element state can only be measured through remote (visual) observation.

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A further illustration of the radically different nature of the L-MCRS stems from consideration of the problem of defining (computing) control rules for the individual robot units. The M-MCRS may rely on the rigidity of joints connecting modules in order to solve the inverse kinematics problem. The D-MCRS needs only to command the individual robots, without taking into account any interaction other than avoiding collisions. For both M-MCRS and D-MCRS, the global control can be assumed to be a composition of the individual control commands, however this is not so for the L-MCRS. For the computation of control commands, an L-MCRS needs to have a model of the passive linking element behavior, which may depend on some physical parameters such as elasticity or weight, and to take it into account to compute the individual robot's control commands. The control on the linking element configuration is, thus, an uncertain and indirect effect of the control of the individual robots, and its response can be highly non-linear. These kinds of problems are new in the robotics literature, and we are starting to deal with them from several points of view.

There are, finally, some natural tasks which can be accomplished by L-MCRS. In some highly unstructured working environments, like shipyards or construction sites, one of the most frequently required operations is the deployment and manipulation of hoses, power-lines, and the like; that is, uni-dimensional objects that serve for the transportation of fluids or power. The automatic deployment, manipulation and transportation of such items poses a broad avenue for research. We have identified and dealt with the following sub-problems in this paper:

- Modeling the geometry and dynamics of a flexible elongated object, that acts as a passive link between the robots. We will call generically this element the "hose". Hose modeling is based on the theory of Geometrically Exact Dynamic Splines (GEDS) [7].
- Modeling and computing the kinematics of the whole system (including the passive link) for its simulation and its inverse kinematics for the derivation of the control commands for the robots from the specification of the desired trajectory. The simulation of the hose–robots system is required in order to design and evaluate control strategies that allow the transport of the hose under different environmental conditions, or control strategies, i.e. following a given trajectory for the leader robot.
- A basic question is: does the L-MCRS have some specific behavior different from a D-MCRS? We give an answer through simulation of the system in Section 4, where it can be appreciated that the linking element dynamics modifies the trajectories of the individual robots from those that would be exhibited by a D-MCRS.
- Development of adaptive control via high level sensory and cognitive mechanisms. Centralized and/or distributed sensing to obtain information on the environment and/or of the configuration of the system including the robots and the hose. We have worked on the development of a Visual Servoing approach, using a Fuzzy Inference System to derive the speed control commands.

The remaining sections in this paper will be as follows: In Section 2 we describe the geometric and dynamic model of the L-MCRS based on the Geometrically Exact Dynamic Splines (GEDS) modeling approach. In Section 4.1 we present the simulation of the L-MCRS hose system which has been used to test some system properties and to explore the potential behavior of a physical realization. In Section 5 we report on a proof-of-concept real life experiment that, although simplified, sheds some light on the difficulties that more extensive efforts will encounter. Finally, Section 6 gives some conclusions and directions for further work.

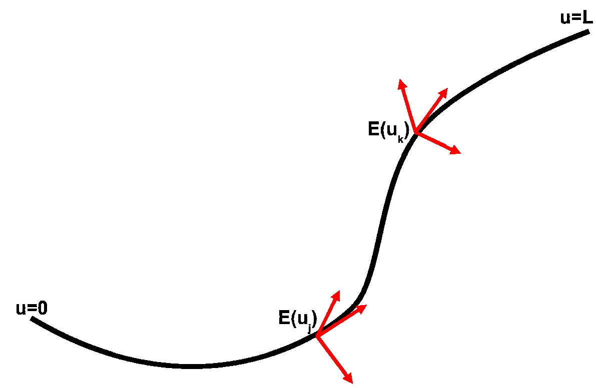

Fig. 1. Cosserat rod model of a hose.

2. L-MCRS geometric and dynamic model

To build up a dynamic model of the whole L-MCRS system, composed of the linking uni-dimensional object and the attached individual robots, we start recalling the GEDS uni-dimensional model in Section 2.1, then we extend this model in Section 2.2 taking into account the attached robots that provide the forces to manipulate the hose. Some previous works on this line were reported in [8,9].

2.1. Linking element geometrical and dynamical model

Modeling uni-dimensional objects has been a subject of research in computer graphics for the representation of wire-like objects with applications in design for industries like car manufacturing or biotechnology/medicine. Several approaches use as the basic formalism differential equations [10], rigid body chains [11] and spring–mass systems [12]. The combination of spline geometrical modeling and physical dynamical models was first introduced by [13], to overcome one inconvenience of the spline model: it is not suitable for representing the hose torsion. The work of [7] has improved the spline representation by combining the spline modeling with Cosserat rod theory, allowing us to model the twisting of the hose. This new approach, known as Geometrically Exact Dynamic Splines (GEDS), represents the control points of the splines by the three Cartesian coordinates plus a fourth coordinate representing the twisting state of the hose.

The Cosserat rod theory [14–16] is usually used in modeling uni-dimensional objects because it permits us to model its physical behavior. In Cosserat rod theory an uni-dimensional object is described by a curve $\mathbf{r}(u)$, the centerline, and a coordinate frame of director vectors $[\mathbf{e}_1(u), \mathbf{e}_2(u), \mathbf{e}_3(u)]$ attached to each point of the curve. The parameter u goes from one end of the curve, for $u = 0$, to the other, for $u = L$, L being the length of the hose. The curve and the director vectors are joined into a coordinate frame $E(u) = [\mathbf{e}_1(u), \mathbf{e}_2(u), \mathbf{e}_3(u), \mathbf{r}(u)]$. A graphic representation of the hose by the curve and the frame director vectors is shown in Fig. 1.

A spline is a piecewise polynomial function. See Fig. 2 for an illustration. The spline expression for a curve $\mathbf{q}(u)$ is a linear combination of control points $\mathbf{p}_i$ where the linear coefficients are the polynomials $N_i(u)$ which depend on the normalized arc-length parameter $u \in [0, 1)$. The following Eq. (1) presents the spline definition:

$$\mathbf{q}(u) = \sum_{i=0}^{n} N_i(u) \cdot \mathbf{p}_i, \tag{1}$$

where $N_i(u)$ is the polynomial associated to the control point $\mathbf{p}_i$, and $\mathbf{q}(u)$ is the point of the curve at the parameter value u.