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Supervisory Model-mediated Teleoperation for Multiple-Master/Multiple-Slave System

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Abstract - This work considers control decomposition problems in multiple-master/multiple-slave (MMMS) systems. The MMMS systems are famous for increased dexterity and higher payload capabilities comparing to conventional systems. Owing to availability of multiple operators it is possible to solve complex tasks that require distributed environment sensing and/or involve additional cognitive load.

We also briefly discuss the problem of communication delay and general approach we going to follow to rectify it.

Keywords - Control decomposition, virtual slave, supervisory control, model-mediated teleoperation.

1. Introduction

Despite the advances in the area of autonomous robotics teleoperated systems still attract a lot of researchers due to complexity of emerging tasks. Amongst these are minimally invasive robotic surgery, deep ocean and space exploration, maintenance and repair works in hazardous environments.

In most of the cases human operators can perform more efficiently than autonomous systems especially when there is a lack of sensory information. Here operator utilizes his/her experience to recognize trends and properties of a system and can predict its future state. Then periodically altering control actions operator can achieve a goal in efficient way.

A vast majority of works for the last few decades were dealing with single-master/single-slave (SMSS) systems (for numerous examples see [1]). However incomparably less research has been conducted on collaborative and cooperative teleoperation [2]. The latter will include single-master/multiple-slave (SMMS), multiple-master/multiple-slave (MMMS) and multiple-master/single-slave (MMSS) systems.

Some of the tasks in teleoperation may require additional mechanical power that cannot be achieved by a single slave robot or may involve manipulation with spatially big objects. Thus, to make such tasks feasible introduction of additional slaves is necessary. So either SMMS or MMMS has to be considered systems. Due to the presence of additional human operators the latter one has several advantages such as higher capabilities in data analysis and increased number of simultaneously controlled parameters. On the other hand MMMS system arrangement requires to solve slave synchronization issue as well as control decomposition problem, in case of *assymetrical* architecture, i.e. where number of operators/masters is not equal to number of slaves or at least where operators do not have direct links to their respective slaves. A typical MMMS system is depicted on Fig. 1.

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2. MMMS architecture

In this work we suggest a new approach to a control of MMMS systems. Effectively we combine SMMS and MMSS system architectures via a *virtual slave* concept. To combine control inputs from operators and to decompose force feedback from the slaves one of control decomposition techniques can be applied, i.e. separate DOF control [3], task-based DOF control [4] or Field of View Deficiency-based (FoVD) decomposition [5]. This additional abstraction layer in turn gives us ability to combine any number of masters with any number of slaves (Fig. 2).

An outlined description of control procedure is as follows:

1. *Separate Control*: While slaves in the system are not interacting they have to be controlled separately or in formations. Therefore either one operator controls his/her own slave or one operator controls several slaves that keep their relative spatial locations with respect to each other.
2. *Kinematic Chain Estimation*: Once a common object

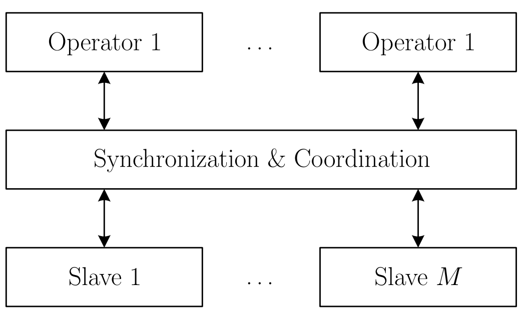

Fig. 1 Schematic representation of typical MMMS system.

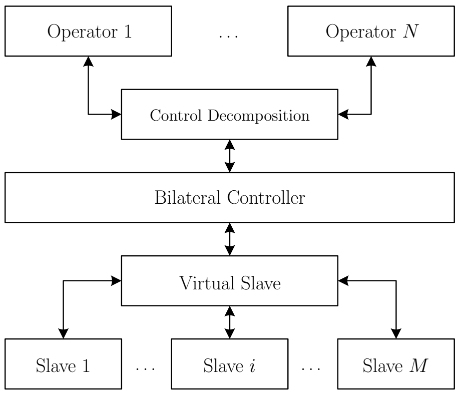

Fig. 2 Asymmetrical MMMS system with Virtual Slave abstraction.

is grasped a new kinematic chain has to be estimated. In case of a rigid object new link can be approximated with a straight bar. Later, while moving, the object its mass and moment of inertia can be estimated as well.

3. *Local Coordination*: Controller on the remote site has to ensure stable local interaction and coordination of the slaves. That can be achieved, for example, with the help of *passive decomposition* [6]. The *locked system*, i.e. *virtual slave* in our terminology, can now interact with masters' site using simple bilateral controller.
4. *Control Decomposition*: On the masters' site the control of virtual slave has to be decomposed with one of already mentioned approaches, i.e. separate DOF control, task-based separation or FoVD-based approach.

One of the main advantages of proposed architecture is that a conventional bilateral controller can be utilized to link local and remote sites. This in turn give us possibility to apply conventional methods to deal with communication delay. On the other hand described architecture only appears at the moment of interaction of slaves and thus cannot be used during the Separate Control stage.

3. Supervisory model-mediated control

Depending on application, delays in teleoperation system may vary from a few milliseconds to several minutes and may be a reason of instability.

According to [7] a control method has to match the level of delay. Thus, for example, to deal with delays under hundreds of milliseconds a passivity-based methods, e.g. wave variable encoding or time-domain passivity, may be applied. While delay grows force feedback becomes useless and even impede control, operators begin to adopt *move-and-wait* strategies and base their decisions only on vision. In presence of very large delays supervisory control approaches can applied.

There are two problems associated with communication delays in teleoperated system – instability caused by phase shift between control input and feedback signals and inability to provide continuous feedback caused by communication delay latency (i.e. time-varying delay).

To rectify this problems we are going to apply *model-mediated teleoperation* approach to our system. The main idea here is to close haptic loop not over a delayed communication channel, but locally on master's site [7]. To generate haptic feedback a model of remote environment is utilized.

Such models can incorporate different properties of the remote objects, i.e. stiffness, mass, kinematic constraints, spatial position and orientation, geometrical parameters etc. Usually such model is not available beforehand and thus has to be estimated from sensory data. Since continues measurements can be affected by delay latency model estimation has to be done locally on slave's site. After that model can be transferred to master's site and continuously updated in sparse time intervals.

Giving some autonomy to remote slave system it is convenient to command back not a continues motion and force commands, but rather high level commands, such as *move forward until contact*, *track surface* etc. Thus, we are organizing supervisory level of control. By further developing this idea we can come to a *teleprogramming* approach [8] that consists in interaction with environment model without sending any commands to slave system straight away. Instead, operator first can try several options manipulating with virtual objects and only after he/she is satisfied with results commit these commands to remote slave.

4. Conclusion

Despite the evident advantages of MMMS systems there is yet not many research done on it. One of the main advantages of such systems is the ability to solve complex task by controlling higher number of parameters by several operators.

In this work we suggest a hybrid architecture of SMMS and MMSS systems and a basic approach to control it. One of the benefits of described architecture is a bilateral link between local and remote sites, but with an ability to control multiple slaves with unequal number of operators.

We also briefly showed our approach to communication delay problem which can be applied to a wide range of delays.

Future work will consider experimental approval of the proposed ideas.

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