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Field of View Deficiency-based Dominance Distribution for Collaborative Teleoperation

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Abstract: This paper intoduces a preliminary study on a new control decomposition criterion for collaborative teleoperation systems – *field of view deficiency*. This criterion represents the amount of visual information available to operators. As a tool for such decomposition we introduce *a dominance distribution matrix* – a more flexible approach to dominance distribution than a well-known scalar dominance factor concept. We introduce collaborative teleoperation architecture, based on field of view deficiency criterion and apply it to experimental dual-master/single-slave teleoperation system. Experimental study demonstrates the effectiveness of the proposed approaches.

Keywords: Teleoperation, collaborative control, dominance distribution, field of view deficiency, multiple-master single-slave, haptic interface.

1. INTRODUCTION

Teleoperation is one of the oldest areas in robotics, which extends human operation range to remote or even virtual environments. There are many application areas such as telesurgery, nuclear waste handling, deep underwater manipulation.

Depending on a task complexity and purpose of the system, the number of operators, master and slave devices may vary. In general, all possible arrangements can be categorized using the following groups: single-master/single-slave (SMSS), multiple-master/single-slave (MMSS), single-master/multiple-slave (SMMS), multiple-master/multiple-slave (MMMS).

The SMSS arrangement is used to be a common approach in teleoperation for a long time. However, in the last two decades, interest to cooperative robotics has risen and gave a start to SMMS and MMMS systems.

Internet-based Ouija board game developed in [1] was one of the first works that considered many-to-one relation in telerobotics, i.e. MMSS architecture. There users collaboratively control remote robot that moves planchette on a board.

Further development of MMSS architecture was urged by the needs of minimal invasive surgery training [2], where trainer and trainee performs a collaborative task on a shared virtual environment [3].

1.1 Dominance Distribution

In conventional MMSS teleoperation system, several operators are intend to produce synergetic motion of a single slave robot by means of multiple master devices. There are several approaches to control MMSS systems, they can be classified, respectively, as *shared* and *decoupled control* of degrees of freedom (DOF).

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The first class of systems corresponds to trainer/trainee architecture, where trainee should follow trainer and mimic all his movements by use of the same control parameters of virtual/real slave device.

Second class, in contrast, implies utilization of different control parameters, thus organizing separate control. For instance, control parameters can be either a separate DOF [4], [5] or separate tasks [6] (e.g. "translational", "rotational", "grasping").

To determine each master's contribution to overall control and/or to demarcate control parameters, a *dominance distribution* concept can be utilized. The definition of *dominance* concept and a review of the works related to it can be found in [7].

A quantitative measure for dominance distribution is a set of complementary *dominance factor* values, such that: $\sum_{i=1}^{N} \alpha_i = 1$, $\alpha_i \in [0, 1]$, where N is a number of masters.

Thus, for a dual-master/single-slave (DMSS) teleoperation system the dominance factors for masters will be α and $1 - \alpha$. In the case of extreme values of dominance factors (e.g. $\alpha = 1$), one operator will dominate over the others and the control of corresponding DOF will be decoupled.

It is necessary to mention here, that one of the most difficult tasks in dominance distribution is the assignment of particular dominance values. However, it was experimentally estimated in [7] that average individual dominance values are much likely to lay in interval of $[0.4, 0.6]$. Authors also pointed out that human operators prefer to experience some dominance difference, rather than work with equally shared control (i.e. $\alpha = 0.5$).

1.2 Our Contribution

One of the major contributions in this paper is proposing of a new control decomposition criterion for collaborative teleoperation based on the amount of visual information available to operators. To the best of our knowledge, so far, none of the researches had involved the amount of sensory data, typically visual information, available to operator in dominance distribution process.

We also extend dominance factor to dominance distribution matrix as a tool for such decomposition. Most of the collaborative teleoperation schemes, so far, have been employing dominance factor as a scalar independent of DOF. This work extends undifferentiated dominance distribution method to differentiated one by introducing diagonal matrix.

2. PROPOSED ARCHITECTURES

A case study of proposed control decomposition approach was conducted on a peg-in-hole task. A straight forward solution for such a task is SMSS system, where operator perceive visual information via 2D picture captured by camera installed on a remote site and receive haptic feedback by means of master device. However, it is well-known that the main disadvantage of such setup is a lack of depth information. Common practice solution for this issue is installation of additional cameras, but such setups are not intuitive for novice.

To overcome this problem we employ an MMSS system, effectively a DMSS, where every operator watching over remote slave system via separate camera and share control with another operator.

A schematic setup of the experimental system is presented on Fig. 1. There, a semi-decoupled visual feedback from *Camera 1* and *Camera 2* is provided to operators via computer screens. Thus, operators observe common workspace from different viewpoints.

Teleoperation system consists of two master devices and one slave, two cameras are installed on the slave site and positioned such that their picture planes are perpendicular to each other. There, Z_sY_s plane of the slave's coordinate frame is coplanar with $X_{c1}Y_{c1}$ plane of the *Camera 1* and slave's X_sY_s plane is coplanar with $X_{c2}Y_{c2}$ plane of *Camera 2*. By neglecting depth information that operators can hardly perceive via perspective deformations, we now can assert that the motion along Y_s axis is the only to coincide for both masters. Thus, the rest of the axes can be fully decoupled in control.

2.1 Field of View Deficiency-based Controller

The following scheme (Fig. 2) implements simple position/force multilateral shared control architecture. The core of proposed system is the *Merging/Dividing and Mapping Block* (MDM), which transforms multilateral control system to a bilateral one. Merging and dividing operations are based on dominance distribution matrix $W_\alpha = diag\{\alpha_x, \alpha_y, \alpha_z\}$ and performed according to equations (1) and (2).

Until now, most of the works regarding dominance distribution were employing one common dominance factor for all DOF. Thus, to extend this concept to multi-DOF slave systems we utilize a diagonal matrix, where each element represents a separate dominance factor per degree. This approach gives more flexibility for sharing control between operators.

The velocities from two master devices are joined together with the help of equation (1), while the feedback force from the slave is split by equation (2).

$$\vec{V}_m = W_\alpha \times \vec{V}^s_{m_1} + (I - W_\alpha) \times \vec{V}^s_{m_2} \ , \qquad (1)$$

where $\vec{V}_m$ is combined velocity vector on the output of MDM block, $\vec{V}^s_{m_1}$, $\vec{V}^s_{m_2}$ – velocity vectors from masters mapped to coordinate frame of the slave, I – identity matrix.

$$\begin{array}{l} \vec{F}^s_{m_1} = W_\alpha \times \vec{F}_m \\ \vec{F}^s_{m_2} = (I - W_\alpha) \times \vec{F}_m \end{array} \ , \qquad (2)$$

where $\vec{F}_m$ is feedback force vector that has to be distributed amongst master devices, $\vec{F}^s_{m_1}$, $\vec{F}^s_{m_2}$ – split feedback force vectors in coordinate frame of the slave.

To deal with misalignment of orientation that exists between coordinate frames of the slave and masters, the mapping (3) is employed. Note, however, that we omit intermediate transformation to camera's frame as its orientation coincides with corresponding master's frame.

$$\begin{array}{l} \vec{V}^s_{m_i} = R_{m_is} \times \vec{V}_{m_i} \\ \vec{F}_{m_i} = R^{-1}_{m_is} \times \vec{F}^s_{m_i} \end{array} \ , \qquad (3)$$

where $\vec{V}_{m_i}$, $\vec{F}_{m_i}$ – velocity and feedback force vectors of i-th master, R_{m_is} – rotation matrix between coordinate frames of the slave and i-th master.

Although there exist translational misalignment as well, it can be neglected since the motion generation in our system is based on displacements, and thus, performed relative to a previous position of the tool tip.

3. EXPERIMENT

To compare the performance of the proposed architecture, an experimental setup according to Fig. 1 was implemented. Two PHANToM Omni were used as master devices and PHANToM Premium 1.5A without stylus was used as a slave. A block with 4 holes in a slanted surface was placed in operation area. A typical peg-in-hole task was set as the objective of control. Thus, human operators were asked to put the tip of the slave to each of the holes in sequence from first to last hole. Human operators can perceive the environment through a video image and through a feel of force feedback generated by the slave. Two web-cameras were used and set up such that their picture planes are perpendicular to each other.

Ten subjects between 19 and 28 years old, students who are majoring mechanical engineering or computer science, were participating in this experiment. The entire subjects were physically and mentally healthy. They did not have any prior information about the hypothesis being tested. Instructions were given, and formal training session was organized for all the participants.

The objective of experiment was to find optimal dominance distribution with respect to proposed control decomposition criteria, i.e. field of view deficiency.

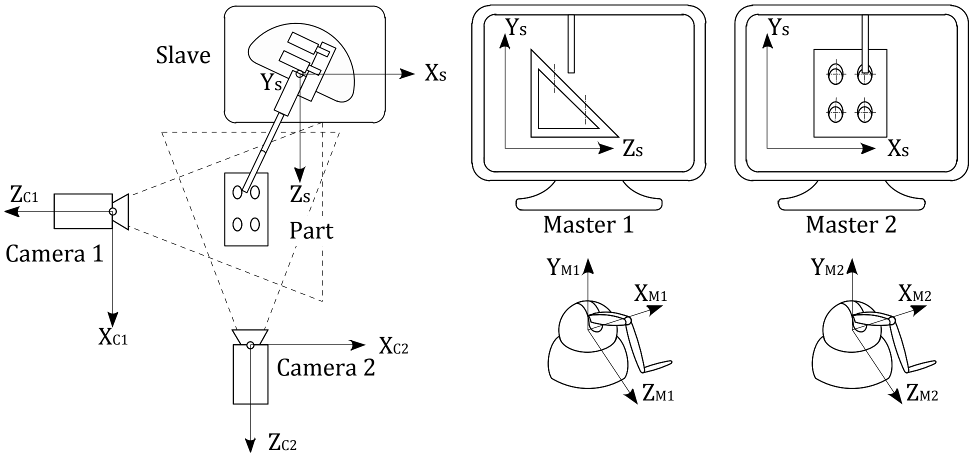

Fig. 1 Semi-decoupled visual feedback in MMSS system. Direction of axis Y for all coordinate frames coincide and is upwards.

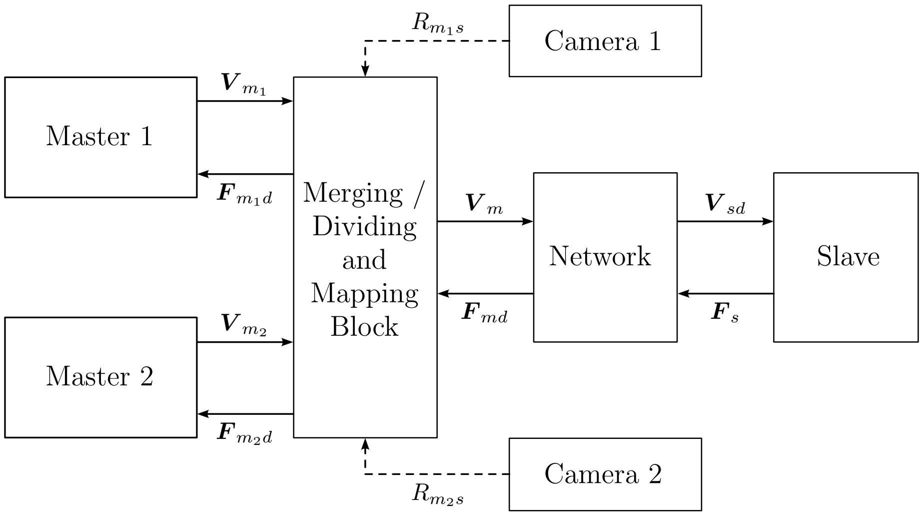

Fig. 2 Simple multilateral control architecture. $\vec{V}_{m_1}$, $\vec{V}_{m_2}$ – velocity vectors generated by masters, $\vec{V}_m$ – combined velocity vector from masters to slave, $\vec{V}_{sd}$ – desired velocity of the slave, $\vec{F}_s$ – force feedback vector generated by the slave. $\vec{F}_{md}$ – common desired force vector for the masters, $\vec{F}_{m_1 d}$, $\vec{F}_{m_2 d}$ – split desired force vectors, $R_{m_1 s}$, $R_{m_2 s}$ – rotation matrices between slave and corresponding masters.

Thus, a session for experiment was conducted. Every configuration was evaluated three times with the following set of dominance distribution matrices (w.r.t. *Master 1*): $W_\alpha = diag\{0.5, 0.5, 0.5\}$, $W_\alpha = diag\{0.2, 0.5, 0.8\}$, $W_\alpha = diag\{0.0, 1.0, 1.0\}$ (fully decoupled control).

To compare performance, average completion time and average number of collisions (between slave's tip and the block) were measured.

3.1 Results

As it can be seen on the graph (Fig. 3), the best performance is achieved by fully decoupled control, there average completion time and number of collisions, respectively: $T_a = 9.46s$, $N_a = 0.23$. Contrary, even distribution of dominance shows the worst results: $T_a = 11.90s$, $N_a = 0.99$. Better results of fully decoupled control are achieved due to the fact that operators work collaboratively, but without disrupting each other intentions, i.e. they do not need to spend time for deciding who should dominate, and who should obey in the task. We can clearly see that dominance distribution based on the proposed field of view deficiency criteria led to the best performance and, therefore, present optimal values of dominance distribution. Here, we can also confirm the results obtained by another research group in [5], i.e. that the separate control of DOF is more effective in collaborative tasks.

4. CONCLUSION

This work introduced a new criterion for collaborative teleoperation. In particular, dominance distribution matrix based on *field of view deficiency* is proposed.

Experimental studies showed that the proposed architecture with dominance distribution matrix and its decomposition method allows higher performance than the conventional architecture, where dominance factor does not consider visual feedback information.

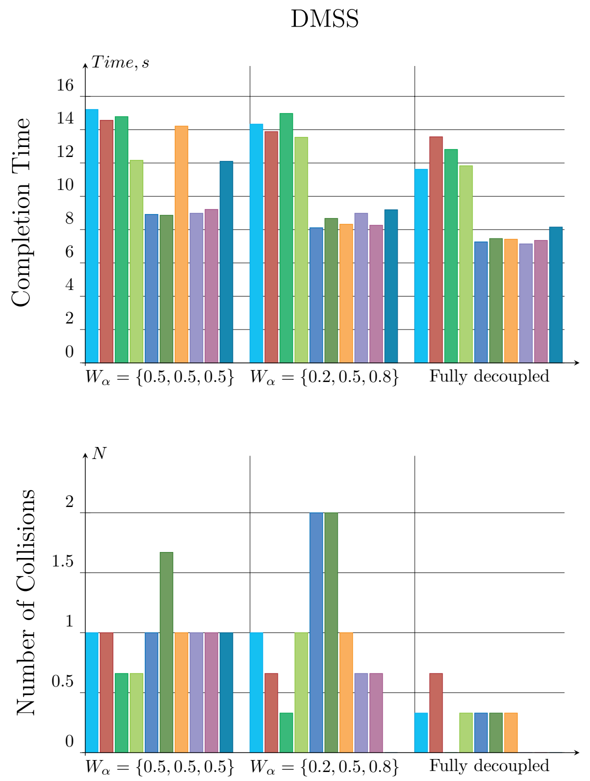

Fig. 3 Comparison of average completion time and average number of collisions between DMSS without (left) and with (right) kinesthetic link.

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