Fuzzy Force-Feedback Augmentation for Manual Control of Multi-Robot System

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***Abstract*—Multi-robot systems represent an enticing area of research with numerous real world applications. Teams of multiple robots can achieve tasks that are more difficult or even impossible for single robot, e.g. environment exploration, search and rescue or surveillance operations. In previous work the authors developed a system for single-operator manual control of multi-robot system. However, such teleoperation systems commonly suffer from inadequate perception of the remote environment. This manuscript extends the previously presented work by adding a fuzzy force-feedback (FFF) augmentation for manual control of multi-robot system. The FFF augmentation delivers additional information to the operator. Moreover, it guides the operator towards a smooth control of the robotic group. The force feedback was generated by a system of fuzzy controllers monitoring the state of the multi-robot group. The performance of the system was evaluated in a virtual environment and the recorded forces were explored in various scenarios. The force feedback augmentation demonstrated the following improvements: i) operator's increased obstacle awareness, and ii) improved maneuvering performance.**

***Index Terms*—Force Feedback, Fuzzy Logic Control, Multi-Robot System, Teleoperation System**

I. Introduction

MULTI-ROBOT systems, commonly referred to as distributive robotics, have been attracting attention of many researchers since the late 1980s [1]. Teaming up of multiple robots introduces redundancy and cooperation into the system, thus making it more robust and flexible [2]-[5]. In many challenging applications, such as environment exploration, search and rescue or surveillance missions, the multi-robot system can deal with tasks often impossible for a single robot.

However, the problem of controlling such a complex system composed of multiple robots is still an unresolved issue and an active area of research. While different autonomously operating multi-robot architectures such as swarm robotics can be found in the literature, the precise manual control of such system has not been explored in much detail yet [5]-[7].

In our previous work, architecture for a manual control of multi-robot system was developed [8]. This multi-robot system was capable of autonomous operation governed by the swarm behavior embedded in each robot [9], [10]. This decentralized control was enhanced by a control signal issued by the operator and broadcasted to all robots. A fuzzy logic controller was embedded in each robot to resolve potential conflicting commands between autonomous swarm behavior and the operator. It was shown that this architecture constitutes a powerful teleoperation scheme for precise control of multi-robot group requiring a single human operator only [8].

However, the teleoperation of complex single or multiple mobile robot systems constitutes a difficult task. The limited amount of information transmitted to the user negatively impacts the perception of the remote environment and leads to imprecise judgment [11], [12]. For example, delivered video-feedback can result in the incorrect depth estimation, disorientation and failure to detect obstacles.

To enhance the operator's sense of telepresence, various haptic interfaces are typically introduced [13]-[17]. These interfaces constitute a new mode of perception of the remote environment. It was shown that additional information such as distance to an obstacle or robots position can significantly improve operator's depth judgment and obstacle awareness [18]. Moreover, applying the force-feedback against operator's motion can further improve the control performance, which can be important in hazardous situations.

In this manuscript, the previously developed architecture for manual control of multi-robot system is augmented by force-feedback. The force-feedback kinesthetic force is generated by a system of fuzzy controllers that monitor the current state of particular robots as well as of the whole group. The operator perceives this force feedback through a haptic device. In the described implementation the force-feedback guides the operator towards smooth control of the multi-robot system. Experimental results demonstrated the generation of the force feedback under various conditions and its contribution to the operator's control performance. Furthermore, it was illustrated that the fuzzy logic controller is a computationally inexpensive and easily adjustable technique for modeling of the force feedback response of the system.

The implemented force feedback can be used for both training of novice users, and assisting experienced operators in coping with difficult maneuvering task in highly

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unstructured environments. The presented systems can be effective in applications such as environment exploration, search and rescue or surveillance operations.

The rest of the manuscript is organized as follows. Section II reviews the previously work. Section III describes the novel fuzzy logic controller architecture for force-feedback generation. Section IV explains the mapping between the degrees of freedom (DOF) of the robotic system and the haptic display. Experimental results are demonstrated in Section V and the paper is concluded in Section VI.

II. Manual Control of Multi-Robot System

This section summarizes the manual control of multi-robot system with built-in swarm behavior introduced in [8].

A. Swarm Behavior Model

The swarm behavior constitutes a decentralized control architecture, where no global information is available to individual robots [19]. Rather than relying on centralized control, robots perceive the local neighborhood and act accordingly. It was shown that despite the lack of centralized group control, global behavioral patterns emerge [20].

In the architecture presented in [8], the swarm behavior model was responsible for low-level navigation tasks such as obstacle avoidance and formation keeping. In this way, navigation tasks were delegated to the swarm behavior itself, enabling operator's manual control of multiple robots as if they were a single entity. The actual implementation of the swarm behavior model was based on the original description by Couzin et.al. [21], following the concept of concentric Local Sensing Zones (LSZs). These zones are illustrated by Fig. 1 (zone of repulsion - ZOR, zone of orientation – ZOO, and zone of attraction - ZOA). If there are robots in ZOR, ZOO or ZOA of particular robot, then the sub-behaviors will be computed as:

$$\vec{v}_R = -\frac{1}{n_{ZOR}} \sum_{j=1}^{n_{ZOR}} \frac{(\vec{p}_j - \vec{p}_i)}{|\vec{p}_j - \vec{p}_i|} \quad (1)$$

$$\vec{v}_A = \frac{1}{n_{ZOA}} \sum_{j=1}^{n_{ZOA}} \frac{(\vec{p}_j - \vec{p}_i)}{|\vec{p}_j - \vec{p}_i|} \quad (2)$$

$$\vec{v}_O = \frac{1}{n_{ZOO}} \sum_{j=1}^{n_{ZOO}} \frac{\vec{v}_j}{|\vec{v}_j|} \quad (3)$$

Here, $\vec{v}_R$, $\vec{v}_O$, $\vec{v}_A$ denote the vectors of repulsion, orientation and attraction sub-behaviors, n_{ZOR}, n_{ZOO}, n_{ZOA} are the number of robots in zones ZOR, ZOO and ZOA respectively, while vector $\vec{p}_j$ represents the position of robot j (robot in one of the three zones). For no robots in particular zone, vectors of repulsion, orientation, and attraction remain simply direction vector of the robot.

Following the sub-behaviors described by Couzin et. al. in [20], robots attempt to avoid the presence of other robots in the ZOR by steering away, robots are attracted by neighbors in the ZOA and try to steer towards their neighbors, and

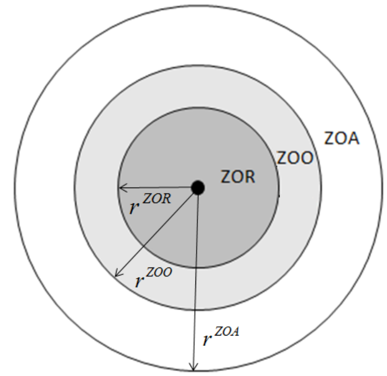

Fig. 1. Local sensing zones (LSZs) maintained by each robot [8].

robots tend to align with neighbors in their ZOO. Finally, if

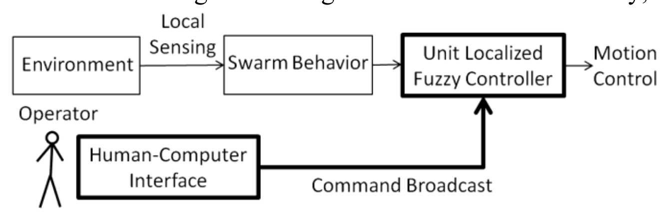

Fig. 2. Motion control mechanism using the fuzzy manual control with build-in swarm behavior [8].

there is an obstacle in the ZOR of particular robot, it attempts to steer away.

The new directional vector of the robot is obtained by weighting and combining the sub-behaviors based on their priority. The obstacle avoidance sub-behavior has the highest priority, followed by the repulsion sub-behavior. Only if there is no obstacle nearby and the robot is not being repelled from its neighbors, it will execute its orientation and attraction sub-behaviors.

B. Fuzzy Manual Control

In our previous work, the control signal was broadcasted from the operator to all the robots [8]. Three DOF (speed, steering and radius of the LSZs) were controlled by the operator. All robots received identical control signal and no data was returned to the operator.

In hazardous situations the manual control was temporarily attenuated allowing the swarm behavior to take over. While the update of speed and radius of LSZs was applied directly to the robot, the steering manual control signal was modified by the fuzzy logic controller and then combined with the swarm behavior model. In this manner, conflicts between operator's intention and the perception of the swarm behavior (e.g. operator's steering of the group against a wall) were resolved. The inputs monitoring the state of the robots were fuzzified using triangular membership functions. The fuzzy inference was performed using min-max rules. For detailed description of the fuzzy controllers used refer to [8]. Fig. 2 shows the designed manual control architecture for multi-robot system.

III. Fuzzy Force Feedback Manual Control Augmentation

This section presents a novel force-feedback manual control augmentation using Fuzzy Logic Controllers (FLCs) for force-feedback enhancement of each of the three DOF of the multi-robot system (speed, direction, radius of the LSZs).

A. Multi-Robot System Analysis

In typical force feedback single-robot teleoperation systems, the generated force resembles the distribution of obstacles in the close proximity of the robot [12], [16], [17]. Hence, the obstacle awareness and the depth judgment of the operator are substantially improved [16]. However, the presented multi-robot system constitutes a more complex case, where additional information can be delivered to the operator in order to reflect the state of the whole group.

The system originally presented in [8] enabled the operator to control the speed, the direction of movement and the radius of the LSZs of the robotic group. Force-feedback augmentation of each of these controllable DOF introduces a bidirectional control system that exchanges forces between the robotic group and the operator. The new system now enables the motions generated by the operator to be translated to the system and used to update the state of particular robots. Consequently, every robot evaluates its current state and its local neighborhood. Based on this information the force feedback is being generated and applied against user's control motion. The augmentation of the three typical DOF of swarm behavior (speed, steering, radius of LSZs) is explained next.

The force-feedback augmentation of *steering* (control of direction of movement), should clearly reflect the location of obstacles in the steering direction. In case of multi-robot systems, the close proximity to an obstacle of a single robot as well as of the whole group should be avoided.

The control of the *radius* of the LSZs directly determines the formation of the group. Here, the force-feedback augmentation should reflect the correctness of particular operator's command. Sudden reduction of the radius may result in disintegration of the group, since the attraction zones stop overlapping. Similarly, radius expansion of the LSZs in small bounded areas may result in a conflict among members of the swarm, since they cannot repel in the constrained space. These restrictions should be translated to the operator in order to prevent unwanted scenarios.

The control of the *speed* is again a typical DOF. Clearly, recovering from inappropriate maneuvers is easier for the operator at lower velocities. Hence, in case of applying the force feedback to steering or merging, the speed should be reduced by generating force-feedback against the operator's control position.

B. FLC for Force-Feedback Generation

The FLC was used for modeling the functional relationship between the state of the swarm and the generated force-feedback [22]. The implemented FLC is of a Mamdani-type [23]. The inputs were fuzzified via evenly spaced triangular input fuzzy sets and a fuzzy rule table, which was experimentally constructed. The actual function is encoded using implicative *if-then* fuzzy rules. The centroid based defuzification was used to produce a crisp output value [24].

The FLC generating the steering force F_S takes two inputs: d_{Obst} - the minimum distance to an obstacle over all robots, and n_{ZOR} - the number of robots having an obstacle in their *ZOR*:

$$F_S = f_S\left(d_{Obst}, n_{ZOR}\right), \tag{4}$$

Here

$$d_{Obst} = \min_{i,k} \left\| p_i - o_k \right\|, \; i = 1 \ldots N, \; j = 1..O \tag{5}$$

Here, the position of particular robot (or obstacle) is denoted by p (or o), where N (or O) is the number of robots (or obstacles), and where operator || || calculates the Euclidean distance. For scenario shown in Fig. 3(a) $d_{Obst} = d_4$ and $n_{ZOR} =$ 2 (robots 2 and 4).

The control surface of this fuzzy controller for normalized inputs is depicted in Fig. 4(a). The implemented fuzzy rules apply higher weight to the d_{Obst} parameter, emphasizing the necessity of single robots keeping safe distance from an obstacle.

The merging force F_M can be computed based on two inputs: d_{Attr} – the maximum distance to the nearest neighbor over all robots being only attracted, and n_{ZOA} - the number of robots being only attracted:

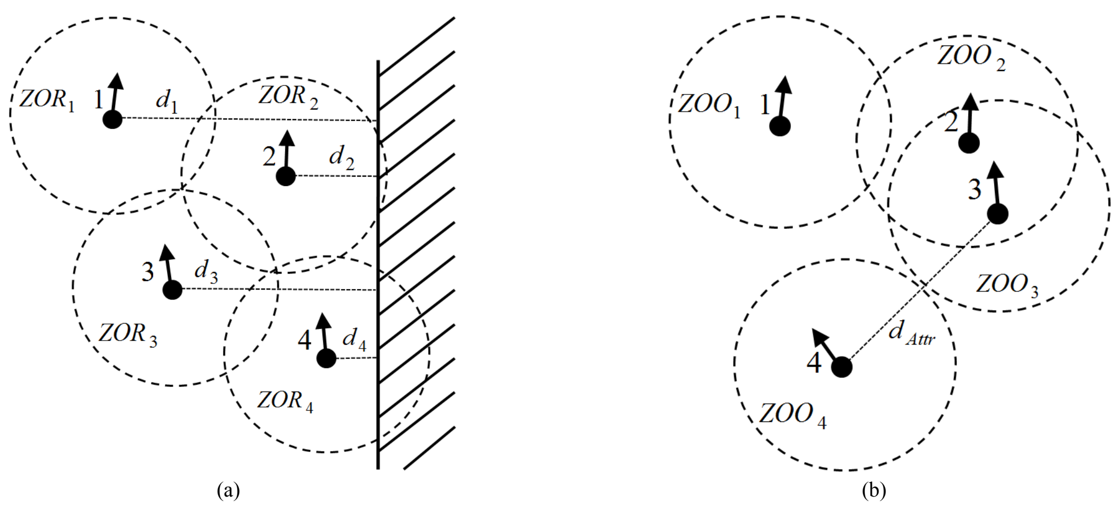

Fig. 3. Calculation of the steering force F_S (a), and the merging force F_M (b).

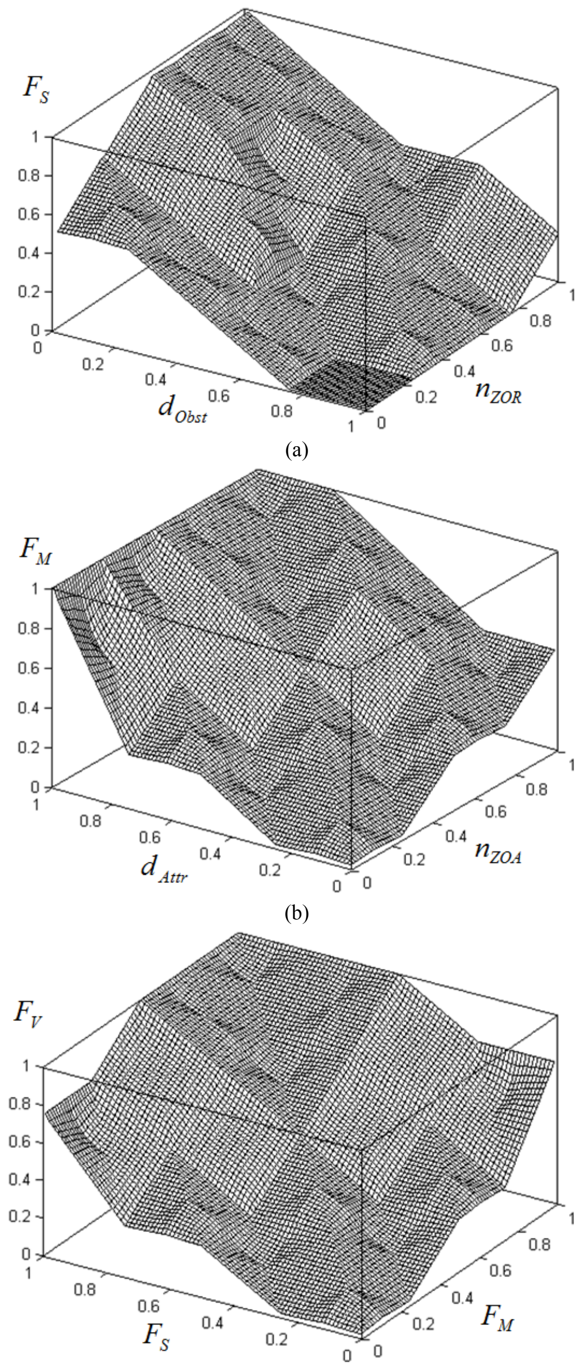

Fig. 4. Fuzzy logic control surface for FLC_S (a), FLC_M (b) and FLC_V (c).

$$F_M = f_M\left(d_{Attr}, n_{ZOA}\right), \tag{6}$$

Here

$$d_{Attr} = \max_i \min_{j, j \neq i} \left\| p_i - p_j \right\|, \forall j, i \in \Omega_{ZOA} \tag{7}$$

Here, symbol Ω_{ZOA} denotes the set of all robots being only attracted. For scenario shown in Fig. 3(b), $n_{ZOA} = 1$ and the distance d_{Attr} is the distance between robots 3 and 4. The response of the fuzzy controller for normalized inputs can be seen in Fig. 4(b).

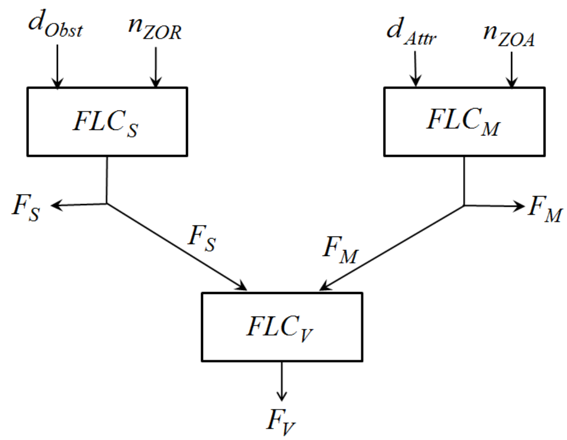

Fig. 5. Structure of fuzzy logic controllers generating the force-feedback.

The speed force F_V needs to be adjusted whenever the robotic group is recovering from an undesired situation. In such situations certain forces F_S or F_M are generated. The force F_V is computed as:

$$F_V = f_V\left(F_S, F_M\right) \tag{8}$$

The described architecture is shown in Fig. 5. The FLC_S, FLC_M and FLC_V blocks are fuzzy logic controllers generating the steering, merging and speed force feedback, respectively. This hierarchical structure enables calculation of the speed force-feedback F_V, based on the steering and merging force-feedback (F_S and F_M). The response of the FLC_V is presented in Fig. 4(c).

C. Force-Feedback Generation

The proposed control architecture of multi-robot system has three DOF. These have to be mapped to an input device that is capable of force-feedback augmentation. The Novint Falcon was used in this work as the haptic display, providing bidirectional communication channel between the operator and the multi-robot system. The Falcon periodically samples the position of the cursor in a 3-dimensional space. Consequently, the kinesthetic force and tactile sensation can be applied against operator's motion.

The degrees of freedom – steering, speed and the radii of LSZs were mapped into the 3-dimensional control space shown in Fig. 6. The sampled position of the cursor C_t at time t is defined as:

$$C_t = \left\{d_t, r_t, s_t\right\} \tag{9}$$

Here, d_t, r_t and s_t are the coordinates along the x (direction), y (radius), and z (speed) axis.

Upon calculating the amplitudes of the forces F_S, F_M and F_V, using (4), (6), and (8), a force feedback needs to be generated and applied to the control axes (x, y, or z). The procedure for generating each of these forces follows.

Steering force F_S should prevent the user from steering towards an obstacle, therefore it needs to be proportional to the calculated amplitude F_S and the displacement d_t of the cursor in the direction axis. The force is applied against the

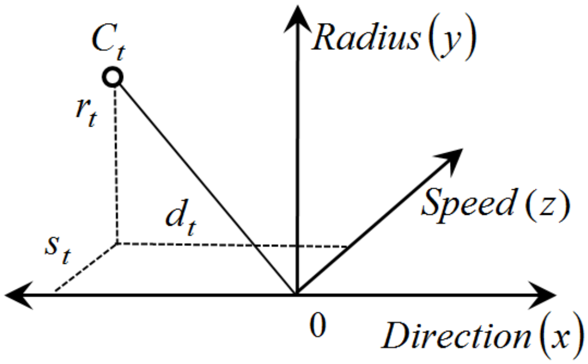

Fig. 6. The mapping of particular degrees of freedom the control space of the haptic display.

(a) (b)

Fig. 7. Virtual environment (a) and the Novint Falcon haptic device (b).

displacement of the cursor. Hence, the applied force F_S^* is computed as:

$$F_S^* = \alpha \, d_t \, F_S \tag{10}$$

Here α is a device dependent normalization coefficient, which scales the displacement d_t and the force F_S into the proper range of force values for the haptic device used.

In a similar manner the generated speed force F_V^* should slow down the motion of the group by guiding operator's hand towards the zero point. Hence, it is proportional to the amplitude F_S and the displacement s_t, along the speed axis:

$$F_V^* = \alpha \, s_t \, F_V \tag{11}$$

Again, α is the normalization coefficient. The force is applied against the displacement of the cursor.

Unlike in the previous two cases, the merging force F_M is not dependent on the actual displacement in the radius axis. Regardless of the cursor position, the applied force F_M^* should directly reflect the force amplitude F_M normalized by the coefficient α :

$$F_M^* = \alpha \, F_M \tag{12}$$

Force F_M^* is applied in the direction of axis y in Fig. 6, preventing the user from inappropriate and too fast reduction of the radius of the LSZs.

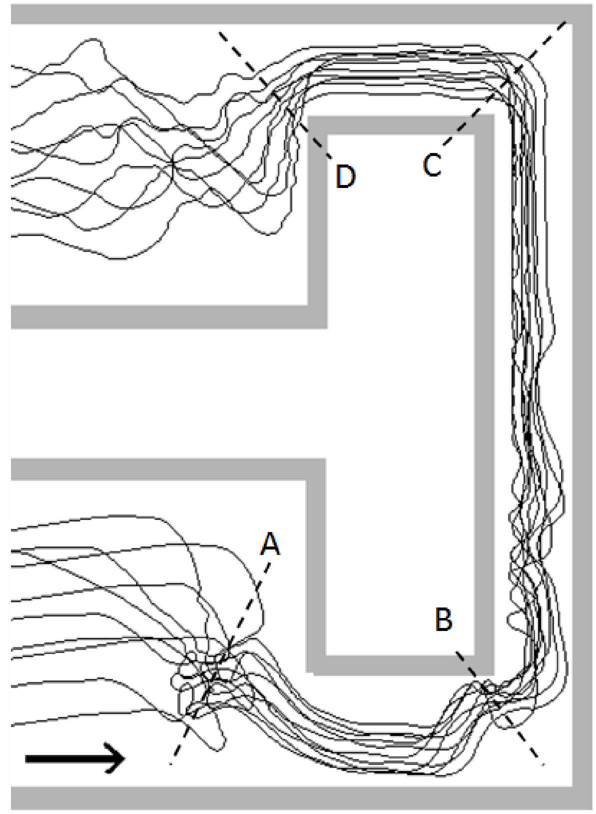

Fig. 8. Trajectories of the units of the multi-robot group as it maneuvers through a narrow corridor (the arrow indicates the direction).

D. Notes on System Stability and Force Interference

Two criteria were considered for the stability assessment of the designed control system. First, the system features stability if every bounded input produces a bounded output. This is inherently ensured by the implemented fuzzy controllers due to their bounded input and output values range. Second, the system features stability if its impulse response converges to zero as time approaches infinity. This is clearly true for the steering forces F_S^* and the velocity force F_V^*. The amplitudes of both forces are proportional to the displacement in particular axis and their direction is towards the zero point. This leads to an eventual decay of the impulse response. Even though the direction of force F_M^* heads in the increasing direction of axis y in Fig. 6, it increases the radius of the LSZs and thus eventually reduces its causation.

In highly unstructured environments with constrained space, the operator may experience application of both the steering and the merging force at the same time. Even though each force is applied along different axis of the control device, certain interference may appear and impair the maneuvering performance of the operator. It should be noted that the FLC_V was implemented to mitigate such effects. The controller contains fuzzy rules, which produce increased velocity force F_V^* when both steering and merging forces are produce. This leads to accelerated speed reduction and thus improves the ability of the operator to cope with such a situation.

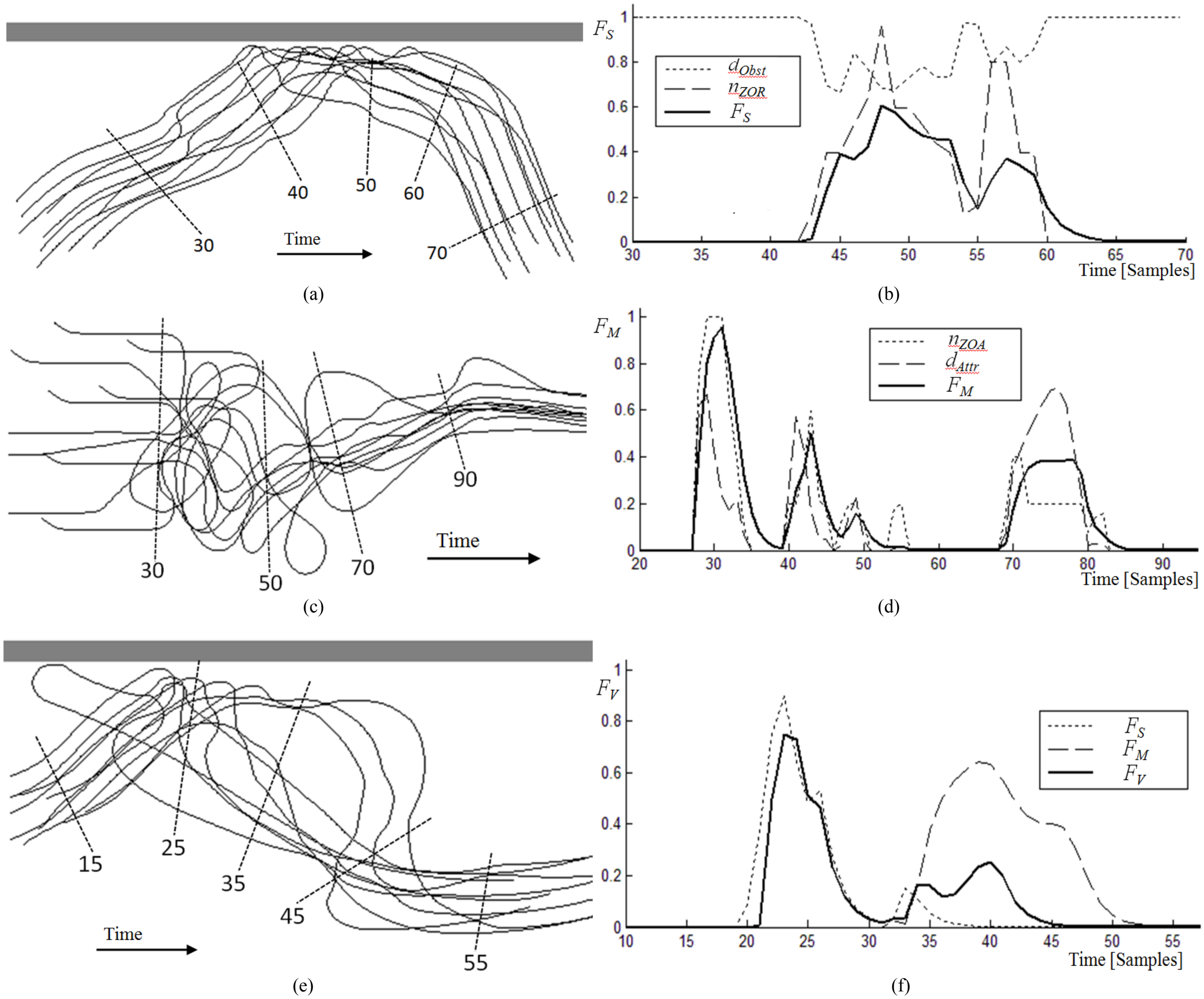

Fig. 9. Recorded trajectories of the robots (a), (c), (e) and the generated force-feedback response of the system (b), (d), (f) during a simple maneuvering scenarions. Dashed lines with numbers in figures (a), (c) and (e) correspond to the time lines in figures (b), (d) and (f).

IV. Experimental Testing

This section describes the implementation of the proposed teleoperation system. Furthermore, the operator's ability to control the system, the behavior of the FLCs in various situations and the contribution of the force feedback are demonstrated.

A. System Implementation

The proposed architecture was implemented in C++ programming language and used in an OpenGL based virtual environment. The virtual environment was interfaced via the Novint Falcon haptic display. This control device has three degrees of freedom that can all be augmented by generated force-feedback or by tactile sensations. Working frequency of 1 kHz and position resolution of 400 dpi within the 4 x 4 x 4 inches workspace enables smooth control of the multi-robot system as well as fluent perception of the generated force.

Fig. 7(a) shows the implemented virtual environment with a group of 10 simulated robots. The robots were denoted by a conical shape to show the direction of movement. Fig 7(b) shows the Novint Falcon haptic device.

B. Manuevering of the Multi-Robot System

In order to evaluate the ability of the operator to control the multi-robot system, a simple testing scenario was designed. During this test, a group of robots performed an environment exploration task. The simulated environment is composed of multiple rooms connected by narrow corridors. The exploration task requires multi-robot group to achieve two conflicting tasks: to cover as much of the space as possible, and to maintain a tight formation when passing through the narrow corridors (possibly pipeline or tunnels).

Fig. 8 shows the recorded trajectories of the multi-robot group which consisted of 10 robots. The operator maneuvers the swarm from the room at the lower left corner of the figure, through the narrow zigzag corridor to the room at the top.

This size of the multi-robot group was arbitrarily chosen based on the relative dimensions of the environment and the virtual robots. In this implementation the diameter of the virtual robots is 20*cm*, while the width of the narrow corridor is 2*m*. The operator was able to accurately steer the robots (B, C). By increasing the radii of the LSZs, the operator instructs the robots to spread out (D). On the other hand, by decreasing the radii of the LSZs, the operator forces the swarm to come together in order to negotiate narrow passages (A). This mechanism enables the operator to control the movement of the group and avoid collisions with obstacles.

C. Generated Force-Feedback

The generated force-feedback was tested in scenarios, when the multi-robot group was intentionally maneuvered into a potentially dangerous situation. The trajectories of individual robots and the inputs to particular FLCs were recorded along with the produced forces. Fig. 9 shows an exemplary maneuvering performance of an operator. The trajectory map in Fig. 9(a), 9(c) and 9(e) can be compared to the response of the fuzzy controllers in Fig. 9(b), 9(d) and 9(f) by matching the marked time events.

Firstly, the behavior of the FLC_S generating the steering force was examined. The response of the controller is displayed in Fig. 9(b). It can be observed that as the swarm is approaching the obstacle, the minimum distance to an obstacle d_{Obst} decreases, while the number of robots close to an obstacle - n_{ZOR} is increasing (in discrete steps). This satisfies the fuzzy rules for determining a potentially dangerous steering situation and the FLC_S generates a smoothly changing force F_S.

Secondly, Fig. 9(d) shows the recorded behavior of the FLC_M generating the merging force. The presented graph displays the maximum distance to a neighbor over all attracted robots d_{Attr} along with the number of robots being only attracted n_{ZOA}. As the radius is suddenly decreased (time sample 30 in Fig. 9(c)), fuzzy rules for determining a potentially dangerous merging situation are satisfied. This is because all of the robots are only attracted and the maximum attraction distance becomes large. Hence, the generated force F_M reaches its maximum. As the robots are recovering from this undesired situation, the force eventually decreases.

Finally, Fig. 9(e) demonstrates the behavior of the FLC_V generating the speed force F_V. As shown in Fig. 4, the FLC_V takes the forces F_S and F_M as inputs and calculates the appropriate response F_V. The behavior of the controller shows how the fuzzy force-feedback produced by controllers FLC_S and FLC_M satisfies the fuzzy rules in controller FLC_V for producing a speed force F_V.

D. Force Feedback Control Improvements

This experiment demonstrates the contribution of the generated force feedback to control of the multi-robot group. Similarly as in [8], the operator has to maneuver a group of 10 robots through a narrow zigzagged corridor. The radius of the LSZs is fixed at a particular value that ensures that the group will be in close proximity of the corridor's wall during the test. The minimum distance of robots to the nearest obstacle was recorded. This testing was first performed with the force feedback augmentation disabled. Next, the testing is repeated with the force feedback turned on, so that the operator can sense the proximity of walls through the haptic display. Histograms are computed from the recorded data.

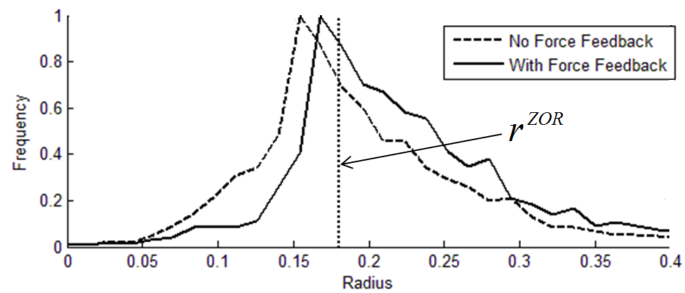

Fig. 10. Normalized histogram of the minimum distance to an obstacle.

Fig. 10 displays envelopes of the computed histograms. For both runs 10.000 samples were recorder during 10 maneuvers through the narrow corridor. The shift between the two data distributions can be clearly observed. When the operator was provided with additional information about the proximity of surrounding obstacles, the robots spent less time near obstacles. This reduces the likelihood of collisions or jams. For comparison, the radius of the local repulsion zone is denoted by a vertical dotted line. The force feedback is applied when robots have obstacle within their repulsion zones.

In conclusion, when the force feedback was applied to the control, the operator managed to navigate substantially better around obstacles. When only visual information was available to the operator, the robots spent considerable amount of time in a close proximity of the obstacles.

V. Conclusion

This paper presented a fuzzy force-feedback augmentation of a manual control of multi-robot system. The presented work extends the previously designed architecture featuring the manual control of the swarm multi-robot system using FLCs built into individual robots. In this initially presented structure, the operator had no force-feedback for telepresence awareness. To alleviate this deficiency, the architecture was augmented by a hierarchical architecture of three FLCs for force-feedback generation. The force-feedback informs the operator about the state of the multi-robot group. This enhancement resulted in increased obstacle awareness, depth judgment and improved control ability.

The proposed architecture was implemented in a virtual environment using OpenGL using the Novint Falcon haptic device. The performance of the system was demonstrated by recording the behavior of particular fuzzy logic controllers in various scenarios. It was shown that the fuzzy logic controllers generated smooth output force and appropriately followed the inputs of the system. The contribution of the force feedback was demonstrated by comparing the histograms of the recorded distances to obstacles during a maneuvering task.

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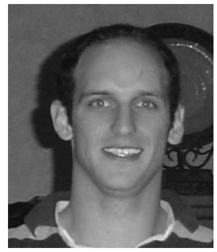

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