Tactile Interaction of Human with Swarm of Nano-Quadrotors augmented with Adaptive Obstacle Avoidance

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ABSTRACT

This paper presents a human-robot interaction strategy to solve multiple agents path planning problem when a human operator guides a formation of quadrotors with impedance control and receives vibrotactile feedback. The proposed approach provides a solution based on a leader-followers architecture with a prescribed formation geometry that adapts dynamically to the environment and the operator. The presented approach takes into account the human hand velocity and changes the formation shape and dynamics accordingly using impedance interlinks simulated between quadrotors. The path generated by a human operator and impedance models is corrected with potential fields

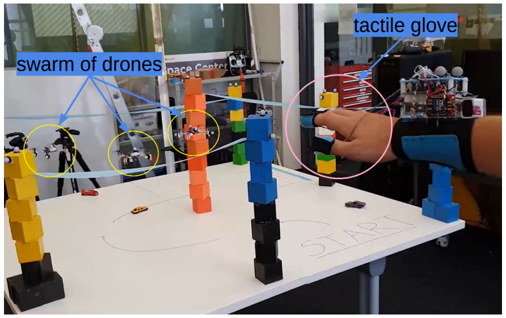

Figure 1: Swarm of three drones guided by a human operator through the labyrinth. Robots change their position according to a human hand movement.

[*] Both authors contributed equally to this research.

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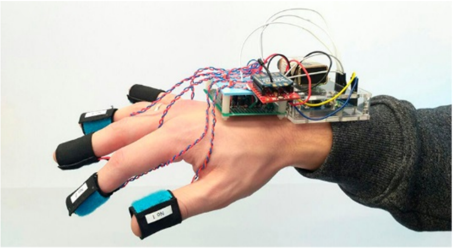
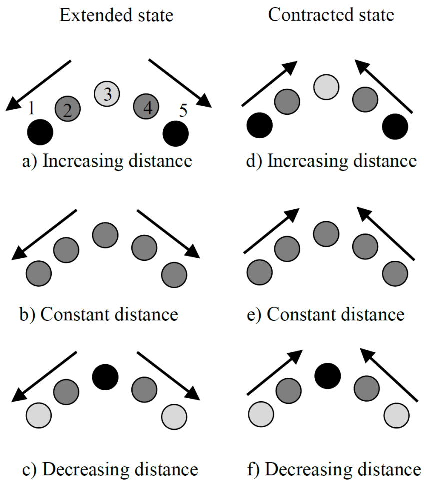


Figure 2: Wearable tactile display.



a) Increasing distance
d) Increasing distance
b) Constant distance
e) Constant distance
c) Decreasing distance
f) Decreasing distance

Figure 3: Tactile patterns for representing the state of the formation in terms of drone-to-drone distance and swarm displacement. Each circle represents the finger of a right hand (view from the dorsal side of the hand). The gray scale color represents the intensity of tactor vibration.

method that ensures robots trajectories to be collision-free, reshaping the geometry of the formation when required by environmental conditions (e.g. narrow passages). The tactile patterns representing the changing dynamics of the swarm are proposed. The user feels the state of the swarm at his fingertips and receives valuable information to improve the controllability of the complex formation. The proposed technology can potentially have a strong impact on the human-swarm interaction, providing a new level of intuitiveness and immersion into the swarm navigation.

CCS CONCEPTS

• **Human-centered computing** → **Laboratory experiments**; **Haptic devices**; • **Networks** → *Network design and planning algorithms.*

KEYWORDS

Human-robot interaction, tactile display, wearable computers, robot formation motion planning, impedance control, potential fields

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INTRODUCTION

Due to a wide range of applications (surveillance, cooperative mapping, etc), multi-agent formations have become one of the most interesting topics in robotic research. The main difficulty for robotic formations is to maintain a pose for each individual agent depending on the poses of other robots and obstacles with a common objective to reach the desired goal. For many kinds of missions, autonomous formation flight is suitable. However, for some specific applications, fully or partially guided group of robots is the only possible solution. The operation of swarm represents a significantly more complicated task as a human has to supervise several agents simultaneously, Fig. 1. In order for the human to work with the drone formation side by side, robust and natural interaction techniques have to be developed and implemented. Human-swarm interaction (HSI) combines many research topics, which are well described by authors in [1]. Here, we focus on the interface (control and feedback) between a human operator (leader) and a swarm of robots, addressing the nascent and dynamic field of HSI.

For the cases when the human is considered as a leader, standard control techniques have been developed in the last decades. Applications could include single robot-human interaction and multi robot-human interaction, both in the framework of centralized and decentralized architectures. A survey [4] shows some of the control approaches. To make human-swarm and human-environment

Percentage, %	**Subject Response**					
Actual pattern	***CD***	***CI***	***CC***	***ED***	***EI***	***EC***
Contracted state, Decreasing distance (CD)	**98.3**	0	0	0	1.7	0
Contracted state, Increasing distance (CI)	3.3	**86.7**	8.3	1.7	0	0
Contracted state, Constant distance (CC)	10.0	5.0	**85.0**	0	0	0
Extended state, Decreasing distance (ED)	1.7	0	0	**86.7**	0	11.7
Extended state, Increasing distance (EI)	3.3	3.3	0	8.3	**66.7**	18.3
Extended state, Constant distance (EC)	0	0	0	3.3	3.3	**93.3**

Figure 4: Confusion matrix for patterns recognition.

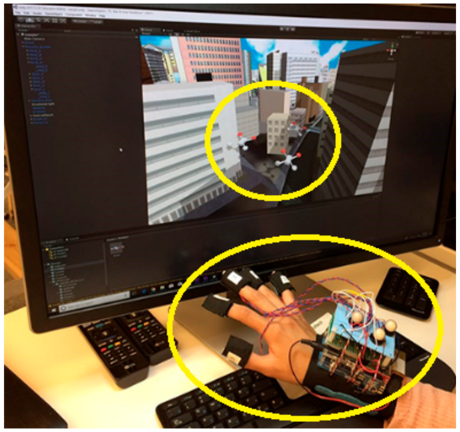

Figure 5: Swarm of drones controlled in virtual reality with the help of the tactile glove.

interaction natural and safe, we have developed impedance interlinks between the agents. In contrast to the traditional impedance control [6], we propose to calculate the external force, applied to the virtual mass of impedance model, in such a way that it is proportional to the human hand velocity. The impedance model generates the desirable trajectory which reacts to the human arm motion in a compliant manner, avoiding rapid acceleration and deceleration.

Changes in the current state of the formation have to be estimated by a human operator. The importance of this statement increases with the number of robots. Haptic feedback can improve the awareness of drone formation state, as reported in [3], [2], and [9]. S. Scheggi et al. [8] proposed the haptic bracelet with vibrotactile feedback to inform an operator about a feasible way to guide a group of mobile robots in terms of motion constraints. In contrast to the discussed works, this paper presents a vibrotactile glove for the interaction of the human with a swarm of aerial robots by providing an intuitive mapping of the formation status to the human finger pads.

In our previous work, [10], we have met the challenges of obstacle avoidance. In order to overcome this problem, the algorithm based on artificial potential fields [7] is proposed in this paper as a local robots trajectories planner.

SWARMGLOVE: VIBROTACTILE WEARABLE DISPLAY

The navigation of the robot with the help of a human operator is inherently a visual process: users identify robots' positions and obstacles through their visual appearance. However, this can get cumbersome and is not feasible in every situation. In particular, if the robot is outside of the user's field of view, occluded by other objects, visual feedback is not enough for reliable control, especially in a 3-dimensional environment, [5]. The main goal of the Vibrotactile Wearable Display usage is the augmentation of human awareness about robots positions and a map.

Tactile patterns

During swarm manipulation by the operator, the formation can change its shape, becoming contracted or extended relative to a predefined geometrical configuration. The state of the formation could be changed due to obstacle avoidance with potential fields or impedance interlinks as described in the lower sections. For such an adaptive formation which could reach dozens or even hundreds of robots, it could be challenging for the operator to estimate the dynamics of the whole fleet. That is why we designed the tactile display SwarmGlove, shown in Fig. 2, and tactile patterns, that could be seen in Fig. 3, for presenting the feeling of the swarm behavior at the operator's fingertips. The glove is equipped with five vibro-motors that become active when the formation shape is getting deformed. The inter-robots distance is presented by the gradient of the tactor vibration intensity (depicted by grayscale shade on Fig. 3). If the formation is extended, then side vibration motors have a higher

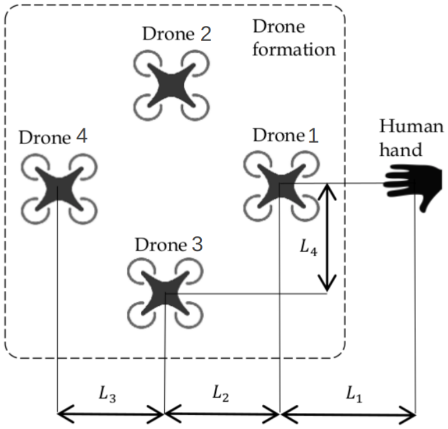

Figure 6: Formation of four drones controlled by a human operator.

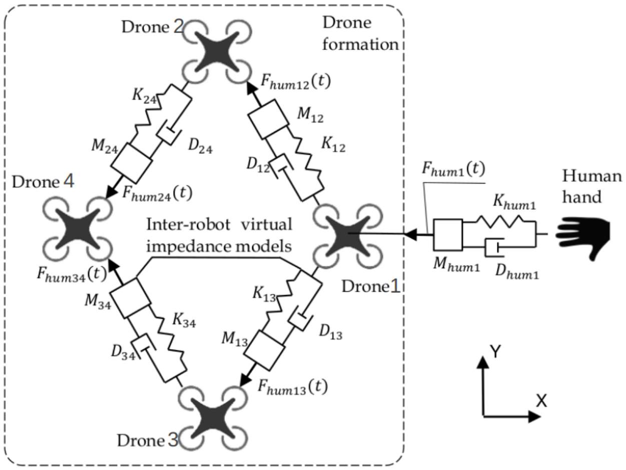

Figure 7: Position-based impedance control links between agents in four drones formation, and human operator and leader drone.

intensity than the middle one. The dynamic change of the distance between robots is presented by the tactile flow propagation, e.g., if the distance is increasing, the flow goes from the middle finger to the side ones (represented by arrows on the Fig. 3).

SwarmGlove experimental evaluation

The experiment was conducted to evaluate the detection of multi-modal patterns. The statistical analysis of the user study revealed the easiest to recognize patterns which were used during the flight evaluation of the tactile interactive display, [10]. The results of the experiment revealed that the mean percent of correct scores for each subject averaged over all six patterns ranged from 78.3 to 96.7 percent, with an over-all group mean of 86.1 percent of correct answers (Fig. 4). The ANOVA results showed a statistically significant difference in the recognition of different patterns ($F(5, 30) = 3.09, p = 0.023 < 0.05$).

During the flight experiments, we used SwarmGlove to deliver the information about the contracted or extended state of the swarm and about the displacement of the formation center of mass. We asked the users to smoothly guide the formation throughout the set of obstacles trying to keep the prescribed shape of swarm using one of two types of feedback: visual and tactile. The results demonstrated that it is possible to navigate the swarm of drones in a cluttered environment using only tactile feedback with low degradation in the quality of navigation. For example, the mean area error (which is defined as default area subtracted with the current area of the formation) for the tactile feedback was 0.01 m^2, while for the visual feedback it was 0.007 m^2.

FORMATION CONTROL

Formation of drones repeats glove trajectory with a spatial scale while being guided by a human operator. Robots' trajectories are also corrected with impedance control technique and an obstacle avoidance algorithm.

Impedance control of the leader-based swarm

To implement the adaptive manipulation of a robotic group by a human operator, such as when the inter-robot distances and formation dynamics change in accordance with the operator state, we propose a position-based impedance control. Mass-spring-damper link between an operator and formation leader (drone 1) is introduced as shown in Fig. 7. External force, applied to the virtual mass of the leader drone, is calculated in such a way that it is proportional to the operator hand velocity. While the operator is guiding the formation in space, impedance models update the goal positions for each flying robot, which changes default drone-to-drone distances. As a result, the operator pushes or pulls virtual masses of inter-robot impedance models, which allows the shape and dynamics of the

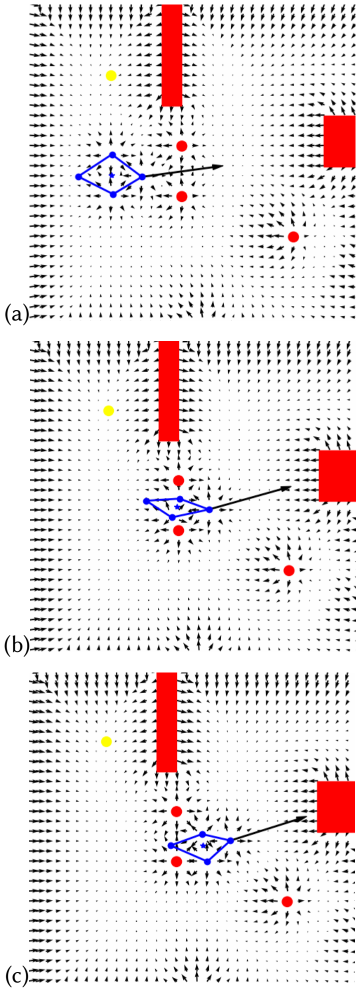

Figure 8: Four robots formation guided through a narrow passage. Potential field map is depicted on each figure (a)-(c) for the left-most drone. A long arrow represents the leader's movement direction.

robotic group to be adaptive in accordance with the human hand movement. In order to calculate the impedance correction term for the robots' goal positions, we have to solve a second-order differential equation (1) that represents the impedance model. Similar equations are solved for each involved pairs of agents as well as for each dimensional axis.

$$M\ddot{\vec{p}}_{imp} + D\dot{\vec{p}}_{imp} + K\vec{p}_{imp} = \vec{F}_v(t), \tag{1}$$

where $\vec{F}_v(t) = K_v\vec{V}_{human}(t)$ is a virtual force, proportional to swarm operator's hand velocity, denoted as $\vec{V}_{human}$, K_v is a scaling coefficient, which determines the effect of the human operator velocity on the formation. The method described above is used to calculate the impedance correction vector, $\vec{p}_{imp} = [x_{imp}, y_{imp}, z_{imp}]^T$, for the current position of the virtual body of each impedance model. The main goal of the proposed impedance control-based model is to make drones trajectories smooth, introducing a delay between the human hand commanded setpoints and robots response. For the case of four controlled drones in the swarm, their goal positions along X, Y, and Z-axis are determined as follows (see the structure presented in Fig. 6, 7):

$$\begin{bmatrix} x_{1\_g} \\ x_{2\_g} \\ x_{3\_g} \\ x_{4\_g} \end{bmatrix} = scale \begin{bmatrix} \Delta x_{hum} \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} x_1 \\ x_1 - L_{12} \\ x_1 - L_{13} \\ \frac{x_2+x_3}{2} - L_{34} \end{bmatrix} - \begin{bmatrix} |x_{imp\_hum1}| \\ |x_{imp\_12}| \\ |x_{imp\_13}| \\ |x_{imp\_24} + x_{imp\_34}| \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} y_{1\_g} \\ y_{2\_g} \\ y_{3\_g} \\ y_{4\_g} \end{bmatrix} = scale \begin{bmatrix} \Delta y_{hum} \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} y_1 \\ y_1 + H_{12} \\ y_1 - H_{13} \\ \frac{y_2+y_3}{2} \end{bmatrix} + \begin{bmatrix} y_{imp\_hum1} \\ y_{imp\_12} \\ y_{imp\_13} \\ y_{imp\_24} + y_{imp\_34} \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} z_{1\_g} \\ z_{2\_g} \\ z_{3\_g} \\ z_{4\_g} \end{bmatrix} = scale \begin{bmatrix} \Delta z_{hum} \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} z_1 \\ z_1 \\ z_1 \\ \frac{z_2+z_3}{2} \end{bmatrix} + \begin{bmatrix} z_{imp\_hum1} \\ z_{imp\_12} \\ z_{imp\_13} \\ z_{imp\_24} + z_{imp\_34} \end{bmatrix} \tag{4}$$

where x_{imp_ij}, y_{imp_ij}, and z_{imp_ij} for $i, j = hum, 1, 2, 3, 4$ are corresponding impedance correction terms, L_{ij} for $i, j = 1, 2, 3, 4$ are displacements for the quadrotors, as could be seen in Fig. 6, and x_i, y_i, z_i for $i = 1, 2, 3, 4$ are the actual positions of UAVs. Equations 2 to 4 consist of three parts. The first part is simply a spacial mapping with the coefficient *scale* between the human position and the formation leader (drone 1) motion, where the values $\Delta x_{hum}, \Delta y_{hum}, \Delta z_{hum}$ denote, how far the human moved his/her hand from an initial position along each Cartesian axis. The second determines the default geometrical shape of the formation (rhomb which is placed in XY-plane in our case), and

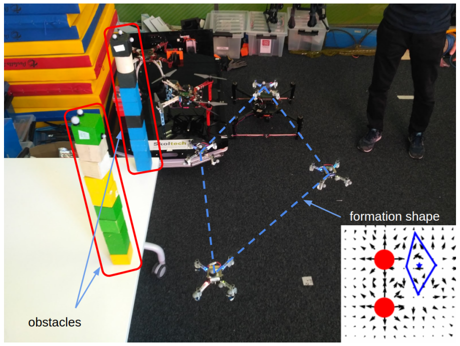

Figure 9: Change of the swarm formation shape due to the presence of obstacles.

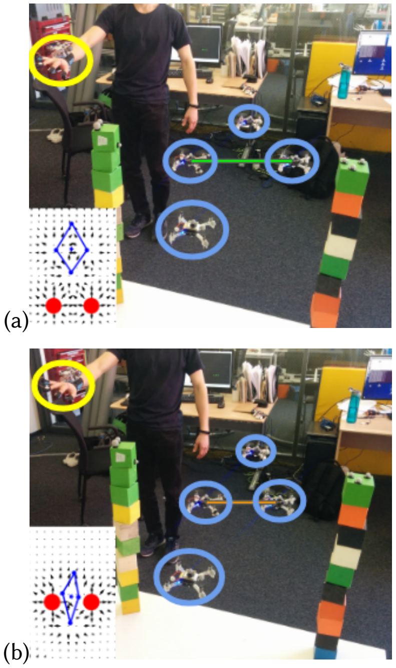

Figure 10: Four drones adaptive formation guided through the passage.

the third describes the impedance interlinks between the agents. The impedance control part of the equations could be designed separately, following the specific application needs. In particular, when the formation is moving fast, we want the drones to always split apart in the negative direction of X axis (from the human), that is why we subtract the absolute values of impedance terms in (2). On the other hand, considering motion in Y and Z axis, the formation has to be shifted in different directions, with respect to the human motion.

Potential fields-based obstacle avoidance

The basic idea of potential fields-based obstacle avoidance algorithm is to construct a smooth function over the extent of robot's configuration space which has high values when the robot is near to an obstacle and lower values when it is further away. This function should have its the lowest value at the desired goal location and its value should increase while moving to configurations that are further away. Ones such a function is constructed, its gradient can be used to guide the robot to the desired configuration [7]. In our case of the human-guided swarm, a point of attraction (desired location) for every drone is defined relative to the leader-drone position with prescribed formation shape. Each robot and obstacle on the known map possesses its own local potential which contributes to the global field. These artificial potentials define interaction forces between neighboring robots and obstacles. Fig. 8 represents four drones formation (blue connected circles) movement through the passage defined by two static obstacles (red circles). Obstacles map is depicted in red, while small black arrows represent here the gradient map for the left-most robot. The algorithm tracks static as well as dynamic obstacles (other drones in the formation).

In the implementation phase, the centralized control approach was used. In this case, one main computer receives all the information through sensors and communicates the decisions directly to the robots. A motion capture system was used to track the drones forming a swarm. Four drones swarm guided through a passage between two static obstacles is depicted in Fig. 10. It can be noticed, that formation adopts its shape in order to avoid collisions, Fig. 9, Fig. 10(b), and drones do not fly too close to obstacles.

CONCLUSION

A novel system has been proposed, which integrates impedance control, potential fields and tactile glove for intuitive and effective swarm control by an operator. The impedance links between agents and adaptive obstacle avoidance algorithm allow the swarm to not only execute safe trajectories but also to exhibit a life-like behavior. We also designed the tactile patterns for the glove and conducted experiments to reveal more distinguishable ones. The possible application of the proposed system is the navigation of swarm in the city with skyscrapers (Fig. 5) and for rescue operations.

REFERENCES

[1] Andreas Kolling et all. 2016. Human interaction with robot swarms: A survey. *IEEE Transactions on Human-Machine Systems* 46, 1 (Feb. 2016), 9–26. https://doi.org/10.1109/THMS.2015.2480801

[2] Hyoung Il Son et all. 2011. Measuring an operator's maneuverability performance in the haptic teleoperation of multiple robots. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*. San Francisco, CA, USA. https://doi.org/10.1109/IROS.2011.6094618

[3] Antonio Franchi, Cristian Secchi, Markus Ryll, Heinrich H. Bulthoff, and Paolo Robuffo Giordano. 2012. Shared Control: Balancing Autonomy and Human Assistance with a Group of Quadrotor UAVs. *IEEE Robotics and Automation Magazine* 29 (Sept. 2012), 57–68. https://doi.org/10.1109/MRA.2012.2205625

[4] Veysel Gazi and Baris Fidan. 2007. Coordination and Control of Multi-agent Dynamic Systems: Models and Approaches. In *International Workshop on Swarm Robotics*. https://doi.org/10.1007/978-3-540-71541-2_6

[5] Sebastian Günther, Florian Müller, Markus Funk, Jan Kirchner, Niloofar Dezfuli, and Max Mühlhäuser. 2018. TactileGlove: Assistive Spatial Guidance in 3D Space through Vibrotactile Navigation. In *The 11th Pervasive Technologies Related to Assistive Environments Conference*. https://doi.org/10.1145/3197768.3197785

[6] Neville Hogan. 1984. Impedance Control: An Approach to Manipulation. In *International Workshop on Swarm Robotics*.

[7] Oussama Khatib. 1986. Real-Time Obstacle Avoidance Avoidance for Manipulators and Mobile Robots. *The International Journal of Robotics Research* 5, 1 (April 1986).

[8] Stefano Scheggi, Fabio Morbidi, and Domenico Prattichizzo. 2014. Human-Robot Formation Control via Visual and Vibrotactile Haptic Feedback. *IEEE Transactions on Haptics* 7, 4 (Oct. 2014). https://doi.org/10.1145/1219092.1219093

[9] Stefano Stramigioli, Robert Mahony, and Peter Corke. 2010. A novel approach to haptic teleoperation of aerial robot vehicles. In *IEEE International Conference on Robotics and Automation*. Anchorage, AK, USA. https://doi.org/10.1109/ROBOT.2010.5509591

[10] Evgeny Tsykunov, Luiza Labazanova, Akerke Tleugazy, and Dzmitry Tsetserukou. 2018. SwarmTouch: Tactile Interaction of Human with Impedance Controlled Swarm of Nano-Quadrotors. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. Madrid. https://doi.org/10.1109/IROS.2018.8594424