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Haptics and Virtual Reality Based Bilateral Telemanipulation of Miniature Aerial Vehicle Over Open Communication Network

Shafiqul Islam, Dongming Gan, Reem Ashour, Paolo Dario, Jorge Dias, Lakmal D. Seneviratne

Abstract— **In this paper, we develop haptic interface system for bilateral telemanipulation of unmanned miniature aerial vehicle (MAV). The proposed interface allows operator to navigate MAV in order to control and interact with uncertain indoor flying environments without using vision systems. The master interface combines bilateral shared control terms with the reflected remote interaction force fields mapped by two different types of force field algorithms as potential force field and spring-damper force field. The shared control strategy for the master comprises velocity signals of the remote MAV with the scaled position of the master haptic manipulator. The bilateral shared input interface for the slave is designed by combining scaled position of the master manipulator with the velocity of the remote MAV. The data transmission between ground station and remote vehicle are carried out by open internet communication network. In contrast with other haptic interface system, the proposed interface system only uses laser technology equipped with the slave MAV. Compared with potential force field based interface, the interface introduced in this paper provides better situational awareness about remote environment helping operator to navigate and control MAV for safe interaction with uncertain indoor dynamic environment. Experimental results together with comparative studies on laboratory made quadrotor MAV are presented to demonstrate the effectiveness of the proposed methods for real-time applications.**

I. INTRODUCTION

In recent years, there is a growing interest in developing advanced aerial robotic systems beyond simple locomotion and observation to physical interactions with various remote objects and environments. In fact, this could extend to MAV operation and manipulation in remote locations to grasp, manipulate, retrieve or carry external payloads or physically interact with objects in rough remote environments. Current advanced autonomous tracking may not be able to perform remote manipulation together with inspection and surveillance tasks precisely and safely, and their tasks demand highly trained human operator. As a matter of fact, unlike autonomous MAV operation, human operators are highly trained and specialized for inspection, manipulation, search, and rescue, and surveillance tasks. Moreover, visual evaluation of the distance between the MAV and the target/obstacle may not be accurate enough to avoid collisions. An experienced autopilot may even fail to achieve precise and safe remote piloting avoiding collisions, as the operator may lack the situational awareness required for remote flying. One of the main challenges in remote operation of MAV is the lake of multiple sensory feedback which affects situational awareness of the operator. Therefore, it is very important to integrate haptic interface based on remote flying environment with the ground operator in order to achieve navigation, control, tracking and interaction such as manipulations and inspections as well as surveillance tasks precisely and safely in uncertain remote environments.

In order to overcome this challenge, initial research in this field utilized mainly vision feedback by either keeping the MAV in line of sight of the operator or using images coming from on board cameras. Most recent results in this direction can be found in [1, 2, 3]. In [1, 2, 3], authors introduced visual feedback based teleoperation strategies for miniature rotorcraft and quadrotor helicopters for indoor environments. However, these designs do not use haptic feedback to maneuver the flying vehicles. Nevertheless, the limited resolution and field of view of on board cameras, high dependence on weather conditions, and high transmission latency of image data, that result in reduced situational awareness. Recent research showed that the use of force feedback in augmentation with vision feedback in teleoperation of MAV can increase safety and performance.

In [4, 5], authors proposed artificial force fields technique from mobile robotic research to map the environment force for haptic feedback for remote operation of the aerial vehicles. Authors in [6] used optical flow from on board camera to generate force feedback to guide the human operator for avoiding collisions of the teleoperated flying vehicle. The method uses an optical impedance mapping approach to generate force feedback from the optical flow field. However, MAV have been used intensively in these designs for outdoor environments with Global position Systems (GPS). Indoor environments are more challenging because flying environments are unknown and unstructured.

To deal with this problem, haptic based shared autonomous systems can be used for indoor navigation and control by using on board laser and camera with the help of haptic perception about the environment. Authors in [7] presented haptic based control algorithm for MAV based on using kinetic scrolling position mapping. This algorithm can be used to overcome the workspace limitation of the master

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S. Islam is with Khalifa University of Science and Technology, Abu Dhabi, 1027788 UAE, and University of Ottawa, Ottawa, Canada K1N6N5.

D. Gan is with Khalifa University of Science and Technology, Abu Dhabi, 1027788 UAE.

R. Ashour is with Khalifa University of Science and Technology, Abu Dhabi, 1027788 UAE.

P. Dario is with Biomedical Engineering and BioRobotics Institute, Scuola Superiore SantAnna (SSSA), Pisa, Italy.

J. Dias is with Khalifa University of Science and Technology, Abu Dhabi,1027788 UAE, and University of Coimbra, Portugal.

L. D. Seneviratne is with Khalifa University of Science and Technology, Abu Dhabi, 1027788 UAE, and King's College London, UK. Contact-sislam@sce.carleton.ca

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haptic device and over large distances in an unbounded workspace of the slave device. In [8] authors However, the feedback force depends only on the distance between the MAV and the obstacles. Recently, authors in [9, 10] proposed teteloperation strategy for quadrotor MAV platform for indoor environments with the help of RGB-D technology. In our view, most reported designs have focused only on avoiding static environments by assuming that passive interaction force from environment can be mapped with the help of vision and laser technology. In this work, our main goal is to use only laser technology to map both passive and nonpassive interaction forces from uncertain remote dynamic environments. We first introduce haptic interface systems by using potential force field (AFF) from the mobile robotic research field. Then, we propose haptic interface based on spring-damper force generated by both spring and spring-damper models. These interfaces can be used to model remote dynamic environments and interaction forces in order to generate haptic feedback as a repulsive force reflecting to the human operator through haptic device. We then integrate haptic interface with bilateral shared control algorithms for master manipulator. The shared control algorithm for master manipulator is designed by combining velocity signals of the remote MAV with the scaled position of the master haptic manipulator. The shared control for the slave is developed by combining scaled position of the master manipulator with the velocity of the remote MAV. We implement and evaluate both haptic based bilateral shared interface system on a laboratory made quadrotor MAV in order to navigate and control MAV in order to interact with the moving environment and reach desired destination safely. The experimental results show that the proposed method could identify the existence of the dynamic obstacles by generating repulsive forces in the opposite direction of quadrotor MAV motion without using vision system. Compared with potential force field based interface, the proposed haptic interface can provide better understanding about remote environment allowing operator to drive MAV safely to desired destination. We also notice from our experimental evaluation that the haptic interface designed by virtual spring-damper models can be used to generate flexible force as opposed to very hard (stiff) force provides by virtual spring model. As a result, the spring-damper based haptic interface allows MAV not only for passive interaction but also for active interaction with moving environment while maintain control and interaction stability of the MAV system.

This paper is organized as follows: In section II, we present model and bilateral shared control algorithms for both master haptic manipulator and remote slave quadrotor MAV. Section III develops haptic interaction interface for bilateral telemanipulation of MAV. Section IV demonstrates experimental results of the proposed method on quadrotor MAV. Section V concludes the paper.

II. MODELING AND BILATERAL SHARED CONTROL ALGORITHM

In this section, we first develop model for designing haptic based shared control and interaction strategy for bilateral telemanipulation of MAV. In our design, human operator commands the desired velocity of the slave inertial frame $\mathcal{B}$. For remote control, tracking and interaction, we consider a Sensable Phantom Omni haptic device with six degrees of freedom (DOF)as depicted in Fig 1 shows complete motion of a 3D rigid body dynamics. It should be noted that we use only three translational and one rotational degree of freedom corresponding to MAV horizontal virtual frame DOF. Let $\mathcal{H} = \{O_{\mathcal{H}}, X_{\mathcal{H}}, Y_{\mathcal{H}}, Z_{\mathcal{H}}\}$ be the haptic device inertial frame and $\mathcal{E} = \{O_{\mathcal{E}}, X_{\mathcal{E}}, Y_{\mathcal{E}}, Z_{\mathcal{E}}\}$ be the haptic device's end effector (gripper) frame. The end effector position and orientation frame in $\mathcal{E}$ is given by:

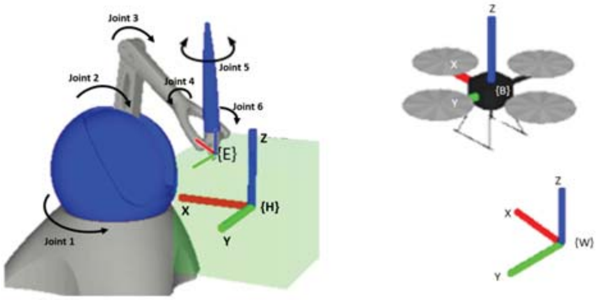

Fig. 1. Co-ordinate transformation model for ground master and remote MAV.

$$\mathbf{x}_m = [x_m, y_m, z_m, q_\psi] \tag{1}$$

The $\dot{\mathbf{x}}_s^d$ is the desired velocity of the robot in frame $\mathcal{B}$ with respect to $\mathcal{H}$ is giving by:

$$\dot{\mathbf{x}}_s^d = k_v \mathbf{x_m} \tag{2}$$

The equations of motion for the 3-DOF haptic device can be written as [13]

$$M_m \ddot{q}_m + B_m \dot{q}_m = F_m + F_h \tag{3}$$

$\ddot{q}_m = [\ddot{x}_m, \ddot{y}_m, \ddot{z}_m]^T$, $\dot{q}_m = [\dot{x}_m, \dot{y}_m, \dot{z}_m]^T$, $q_m = [x_m, y_m, z_m]^T$ are the joint acceleration, velocity and position, respectively, expressed in frame $\mathcal{A}$, $M_m \in \Re^{3\times3}$ is the diagonal symmetric positive definite inertia matrix, $B_m \Re^{3\times3}$ is the diagonal matrix of damping coefficient, $F_m \in \Re^{3\times1}$ is control force vector and $F_h \in \Re^n$ denotes operational human force vector applied to the haptic device by the human operator from ground station. We now derive shared input algorithm for the master haptic manipulator with the input interaction forces. We design the master control law where master device interfaces with the flying slave MAV interacting with remote environment F_E. The bilateral shared input for master system combines velocity signals of the remote MAV with the scaled position of the master haptic manipulator and remote environment interaction force F_E as defined as follows

$$F_m = K_{ph} \left(\dot{q}_s - S q_m(t) \right) - F_E \tag{4}$$

where the scaling factor S is defined as

$$S = \frac{abs\,(max(q_s) - min(q_s))}{abs\,(max(q_m) - min(q_m))} \tag{5}$$

where $K_{ph} \in \Re^{3\times3}$ is the proportional gain. The terms F_E is the interaction feedback between remote environment and quadrotor MAV to the human operator allowing the human operator to map remote environment based on laser technology. In our design, the interaction environment force F_E as derived in next section is designed by using both potential force field and spring-damper force field for mapping uncertain remote environment.

Let us now model and develop bilateral shared control strategy for the slave system. In our case, quadrotor MAV is used as remote slave system. Before implementing the shared control algorithm, it is essential to design stable control system for attitude and position dynamics. Like existing design, we assume that the attitude dynamics is faster than the position dynamics [14, 15, 16]. This condition is, in fact, realistic for quadrotor MAV that can be achieved by designing control design parameters. To develop shared control algorithm, we model quadrotor MAV by using the following differential equation

$$\ddot{x} = \frac{u_1}{m}\left(\cos\phi\sin\theta\cos\varphi + \sin\varphi\sin\phi\right) \tag{6}$$

$$\ddot{y} = \frac{u_1}{m}\left(\cos\phi\sin\theta\sin\varphi - \sin\phi\cos\varphi\right) \tag{7}$$

$$\ddot{z} = -g + \frac{u_1}{m}\left(\cos\phi\cos\theta\right) \tag{8}$$

$$\ddot{\phi} = \frac{u_2}{I_{xx}}, \ddot{\theta} = \frac{u_3}{I_{yy}}, \ddot{\varphi} = \frac{u_4}{I_{zz}}, \tag{9}$$

where u_i with $i = 1, 2, 3, 4$ is the control input, and I_{xx}, I_{yy} and I_{zz} represent the moment of inertia with respect to x, y and z axes, respectively. The cross of inertia are assumed to be zero as they are very small and $I_{xx} \approx I_{yy}$ due to symmetry. The controller is designed by linearizing the quadrotor model at the hover state $x = x_0$, $y = y_0$, $z = z_0$, $\phi = 0$, $\theta = 0$, $\varphi = \varphi_0$, $\dot{x} = 0$, $\dot{y} = 0$, $\dot{z} = 0$, $\dot{\phi} = 0$, $\dot{\theta} = 0$, $\dot{\varphi} = \varphi_0$. So, by assuming small roll and pitch angles, we can write $\cos\phi \approx 1$, $\cos\theta \approx 1$, $\sin\phi \approx \phi$ and $\sin\theta \approx \theta$. Then, we use the following PD algorithm to calculate the control moment for attitude dynamics [15]

$$\begin{aligned} &u_2 = -K_{p\phi}\phi(t) - K_{d\phi}\dot{\phi}(t), u_3 = -K_{p\theta}\theta(t) - K_{d\theta}\dot{\theta}(t) \\ &u_4 = -K_{p\varphi}\varphi(t) - K_{d\varphi}\dot{\varphi}(t) \end{aligned} \tag{10}$$

with $K_{p\phi} > 0$, $K_{p\theta} > 0$, $K_{p\varphi} > 0$, $K_{d\phi} > 0$, $K_{d\theta} > 0$ and $K_{d\varphi} > 0$. Then, we design bilateral shared input for the slave quadrotor MAV by coupling scaled position of the master manipulator with the velocity of the remote quadrotor MAV as given as follows

$$F_s = K_{ps}\left(-\dot{q}_s + Sq_m(t)\right) \tag{11}$$

$K_{ps} \in \Re^{3\times3}$ and $q_s \in \Re^{3\times1}$.

III. SHARED HAPTIC INTERACTION INTERFACE SYSTEM WITH UNCERTAIN DYNAMIC ENVIRONMENTS

In this section, we introduce haptic interaction force feedback term F_E in (4) for passive and nonpassive interaction with uncertain remote environments. The remote environment interaction force F_E is designed by using potential force field and spring-damper force field with spring and spring-damper model. F_E can map remote environment constraints and reflect to the human operator hand as repulsive force. More precisely, in the presence of uncertain remote environments, haptic feedback can provide a human operator an impedance force sensing corresponding to the repulsive forces through a haptic device enabling the operator either to avoid or direct interact with environments performing specific tasks safely and perfectly. In fact, the transmitted interaction force provides human operator awareness about remote environment situation. In this work, we compare the proposed spring-damper force field based haptic interface with potential force field feedback for navigation, control and tracking for highly uncertain MAV for passive and nonpassive interaction with uncertain dynamic environments.

A. Potential force field based haptic interface design

Let us first design and analyze the popular potential force field for haptic interaction between human and remote environments via local master and remote MAV. Potential force field is generated from the potential field which was introduced in [11] for the unmanned ground vehicle. This method only depends on the distance between the ground vehicle and environments. The repulsive forces are generated by taking the gradient of the potential field. This method has some drawback where the repulsive forces will be generated in all situations even if the ground vehicle is neither moving nor moving away from the environments. Later author in [12] extended the concept of potential field making it more generalized by including the relative velocity of the vehicle with respect to the environments. This generalized method is known in the field of mobile robotic research as generalized potential field (GPF). The GPF depends on the reverse time that is the difference between maximum and minimum time the vehicles needs to stop before colliding with environments. However, the GPF approach has a several drawbacks such as if the reverse time approaches zero, then the potential field will goes to infinity. On the other hand, the method only maps the environments in the direction of motion. Moreover, this design may be unrealistic for real-time application due to the hardware limitations. Recently, author in [4,5] introduced the basic risk field (BRF) which limits the values of the potential field to an upper boundary making the potential field depends on the reverse distance (the difference between the maximum and minimum breaking distance) and the vehicle velocity. Here, the potential field serves as a risk field. The risk is usually limited between lower and higher risk. However, BRF has a drawback in the narrow places when moving with high velocity generating very large potential field. Later author in [4,5] modified their BRF design to the parametric risk field (PRF). In fact, the PRF allows the change of the size and the shape of the potential field. The field is defined as protection zone, the critical region, area between the inner and outer boundary and outside the outer boundary. In this case, the potential field is calculated by the rate of change of the risk value that is defined by the d/d0 (d is the shortest distance between the environment and the critical region, d0 is the distance between the critical region and the outer boundary). The field depends only on the position and the vehicle velocity. The repulsive forces obtain by taking the gradient of the potential field. However, the PRF with normal risk vector generates very high oscillation when the vehicle flies close to the environment. The BRF can be calculated by limiting the values of the potential field to an upper boundary resulting in the potential function as [4] [5]

$$BRF = \begin{cases} 1 & d_{res}(d, v_i) \leq 0, 1\frac{1+v_i}{d_{res}(d,v_i)} \geq \frac{1}{G} \\ 0 & \frac{1+v_i}{d_{res}(d,v_i)} \leq 0 \\ G\frac{1+v_i}{dres(v_i,d))} & otherwise \end{cases} \tag{12}$$

where BRF is the basic risk field, $d_{stop} = \frac{v_i^2}{2a_{max}}$, v_i is the velocity towards an environment, d is the distance from the environment, G is the gain that limits the BRF to certain bound, and $d_{res}(d, v_i)$ represents reserve avoidance distance.

Let us now develop spring-damper force field based haptic interface for bilateral telemanipulation of MAV. The proposed interface allows human operator to understand environments around remote MAV providing guidance for navigation, remote presence, control, tracking and interaction with environments. The relation between vehicle and environment is modeled by using both virtual spring and spring-damper models. The interaction feedback force from the spring-damper model is mapped and reflected back to operator hand via haptic device in order to interpret the environment situation around the flying vehicle. The virtual interaction force feedback for the human operator can be mapped by using both static and dynamic environments according to the method proposed as

$$SD(i) = \Sigma_{i=0}^{N_s} f_s(i) + \Sigma_{i=0}^{N_s} f_d(i) \tag{13}$$

where N_s defines the number of static and dynamic obstacles, f_s and f_d can be calculated by using virtual spring-damper models.

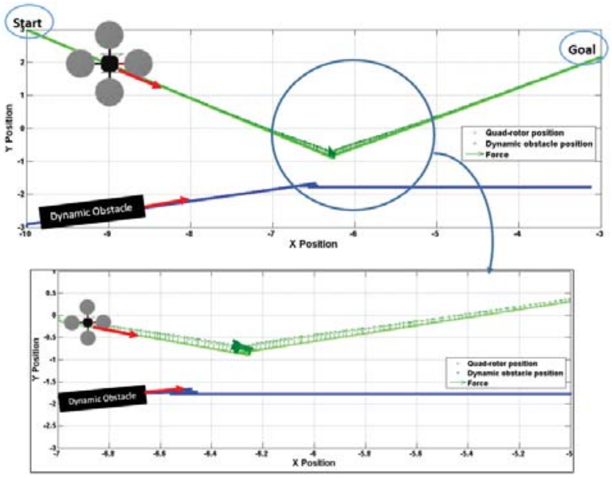

Fig. 2. Figure shows quadotor MAV actual position, moving environments and interaction forces between the vehicle and environments under BRF potential force field method.

IV. Experimental Results

In this section, we implement and evaluate the proposed bilateral shared autonomous strategy on laboratory made MAV for navigation, control and interaction with uncertain dynamical environments. We first describe the scenario along with experimental setup that used for conducting the experiment. Then, we compare the interaction behavior of the haptic interface designed by using both potential and spring-damper force field methods. The experiment consisted of the master system, quadrotor MAV system, communication network system, haptic interface system, shared control system and interaction environments. From our various test scenarios, we only present experimental results for one scenario for the sake of simplicity and page constraint. In this experiment, we consider a dynamic moving environment where quadrotor flies against time varying uncertain wave like environment. The quadrotor MAV starts from an initial position and reach desired destination while tracking and interacting directly with moving environments structure.

We conduct experiment in indoor flying environment where operator remotely control quadotor MAV and interact with uncertain dynamic environment. In our experiment, the position and attitude of the vehicle is obtained from Gazebo and Robotic operating system (ROS). Virtual simulator Gazebo was used in this experiment to develop dynamic environment based on using laser sensor equipped with MAV. To test the proposed shared autonomous strategy, we first need to ensure the quadrotor MAV remain stable over wide range of operating points. We have used PD control algorithm as presented in [15]. The vehicle is controlled to hover from rest, then from hovering flight to take-off, then free flight control and from free flight to hovering flight.

The components used in our experimental setup are operator, master manipulator, slave manipulator, interaction force models, bilateral master and slave control, interaction environment and communication networks. The operator uses the haptic device in order to teledrive MAV. To understand world around the vehicle, haptic interface is designed to interact with human operator through haptic device. The master is a 3-DOF phantom manipulator provided by SensAble Inc. The position of the haptic device is measured by optical encoder. ROS together with the haptic toolkit is used to develop model, shared autonomous controller and interaction interface system for phantom haptic manipulator. The remote slave platform is a laboratory made quadrotor MAV. ROS and Gazebo simulator is used to develop model and control for the quadrotor MAV. In our test, the velocity of the quadrotor is set to $1m/s^2$. A laser range finder sensor was used in order to locate the environment.

Before applying shared control and interaction strategy, it

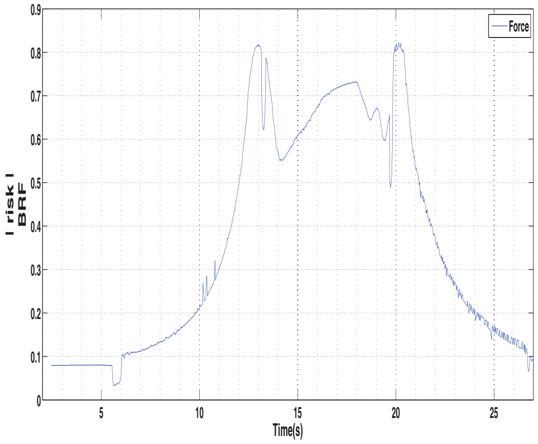

Fig. 3. Magnitude of the normal risk vector under BRF based potential force field method.

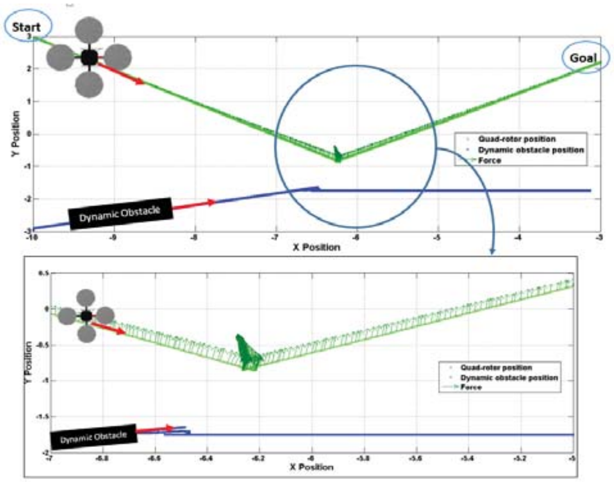

Fig. 4. Figure shows quadotor MAV actual position, moving environments and interaction forces between the vehicle and environments under proposed virtual spring-damper model based method.

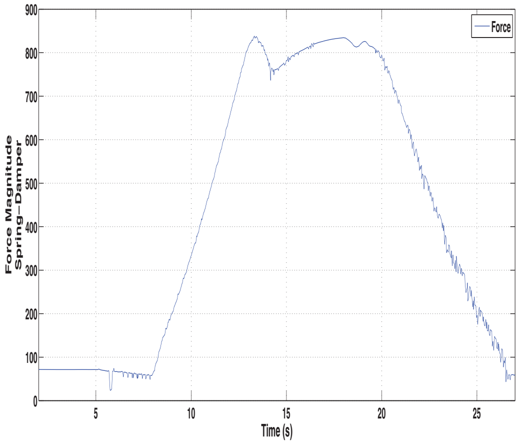

Fig. 5. Magnitude of the interaction force under proposed virtual spring-damper model.

is essential to ensure stability of the quadrotor MAV. Both master and slave controllers developed in previous section is implemented in ROS using c++ language. The parameters for the proportional gains for the master controller are $K_{phx} = 1.0$, $K_{phy} = 1.0$, and $K_{phz} = 1.0$ while the proportional gains for the slave controller are $K_{psx} = 1.0$, $K_{psy} = 1.0$, and $K_{psz} = 1.0$. The design and implementation strategies for attitude controller are followed as given in [15]. Potential and spring-damper force field model uses the data from the laser finder to develop haptic interaction interface for human operator. The gain parameter for potential force field G is set to 0.1. The parameters for the spring-damper are chosen as $K_{sx} = 1.0$, $K_{sy} = 1.0$, and $K_{sz} = 1.0$, $D_{sx} = 10.0$, $D_{sy} = 10.0$, and $D_{sz} = 10.0$. In this experiment, the environments are assumed to be dynamic and uncertain. The operator does not know the exact location of these environments in the real-world as the slave MAV does not equip with vision system. Our aim is to drive the quadrotor MAV by using only haptic interface based virtual simulator created in ground station. The data transmission between master and remote slave MAV is done by using internet. The communication delays between ground station and remote MAV are assumed to be negligible as they are connected in the same network.

We first implementation results for haptic interface systems designed by using BRF based potential field. Implementation results are presented in Figs. 2 to 3. The position of the quadrotor MAV is represented in green x's and the position of the dynamic environments are represented as blue x's. The arrows represents the total interaction force feedback vector. Fig. 2 shows that the forces are only generated when the environments appeared and the MAV are getting closer to each other but not when they are getting far away. From Fig. 3, we can see that the maximum risk vector is achieved when the MAV collide with the environment. Notice also from Fig. 3 that MAV moved in a stable manner, except for BRF with normal risk vectors, where a collision with environment with large oscillation occured. In view of this results, we can see that the haptic interface based on BRF method does not render interaction forces that can provide operator situational awareness in order to stop MAV before it collide with the environment.

Let us now implement haptic interface system designed by using spring-damper model. For fair comparison, the dynamic environments, tracking tasks, control algorithms and all other design parameters for the MAV are kept similar to our previous experiment where both environments and vehicles are flying with moving wave like environment structure. Evaluation results are depicted in Figs. 4 to 5. Fig. 4 shows the tracking trajectory of the quadrotor and the environment. When the environments are moving closer to the quadrotor and, at the same time, the quadrotor is moving toward the dynamic environments, the interaction feedback force vector increases gradually and uniformly to reach its maximum corresponding to the closest point. Then, it starts to decrease reaching to zero when the environments and the quadrotor are moving away from each other. When vehicles and environments comes closer again, the interaction force feedback starts to increase again. This time the magnitude of the interaction force is smaller than the previous time. This is due the fact that the distance between the environments and the quadrotor is less than the previous time. Fig. 4 also shows the direction of the interaction force which is always in the opposite direction of the quadrotor motion. Fig. 5 shows the magnitude of the interaction force between the vehicle and environments. We can notice from this results that the haptic interface designed by virtual spring-damper can render remote interaction forces between MAV and environment to the operator hand providing situational awareness around the flying vehicle to navigate and control MAV safely without collision.

V. CONCLUSION

In this paper, we presented haptic based bilateral telemanipulation strategy for MAV for remote navigation, control, tracking and interaction with uncertain environments. We have proposed spring-damper force field based haptic interface system. We also experimentally analyzed potential force field based haptic interfaces for comparison purpose. The properties of both interfaces investigated in the presence of dynamic environments without using vision system equipped with slave MAV while it flies in uncertain dynamic environment. The experimental results showed that the interaction force designed by spring-damper system provides a better understanding of the remote environment around the flying vehicle allowing operator to navigate, control, interact with cluttered environment and track MAV safely to reach desired destination. Unlike potential force field mechanism, haptic interface designed by spring-damper model provides better situational awareness about the remote environment. In our future work, the proposed haptic interface based shared autonomous system will be investigated in the presence of the data transmission delays between ground station and remote quadrotor MAV.

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