lines) demonstrates that a drone position controller could track the desired trajectory accurately.

To demonstrate the performance of the proposed algorithm for the formation guidance, first of all, we refer to Fig. 5, where a human moves their hand from the right to the left. This figure presents an interesting feature of the impedance control. While the human starts to move fast, the formation immediately spreads along human movement direction like a spring. This example demonstrates that the formation adapts to human, right after the operator starts to move its hand. When the human hand velocity starts to decrease, the formation contracts back to the initial shape. The axis, along which the formation changes its shape, coincides with the human velocity vector; therefore, when the human changes the direction of movement, the formation adapts accordingly. Fig. 6 shows distance along the Y-axis between Drone 1 and Drone 4, which are placed in accordance with Fig. 2. The displacement between drones is displayed in Fig. 7. Here one can see that the magnitude of the displacement is increasing for drones farther away from the human. To meet that issue, in the future work, the stability of the proposed method will be considered with the increased number of drones.

The proposed control algorithm could be used not only for human-swarm interaction (HSI) but also for obstacle/collision avoidance. On the other hand, HSI could significantly benefit if we couple described control method with tactile feedback, forming an interface (control and feedback) between a human and a formation. Informing a human operator about the dynamic formation state (extension or contraction) at the current time could potentially improve controllability.

2.4 Obstacle avoidance with impedance control

Apart from internal factors that affect the swarm state, such as mass-spring-damper links between the drones, there also could be external reasons which could lead to the formation change, e.g. obstacles. We assume that, within the swarm, every agent makes a decision on where to go next basing both on local information about surroundings and on global goal (derection of motion). In such a scenario, each quadrotor could plan its obstacle avoidance considering the position of nearest obstacles and neighbor agents. The planning algorithm is described below.

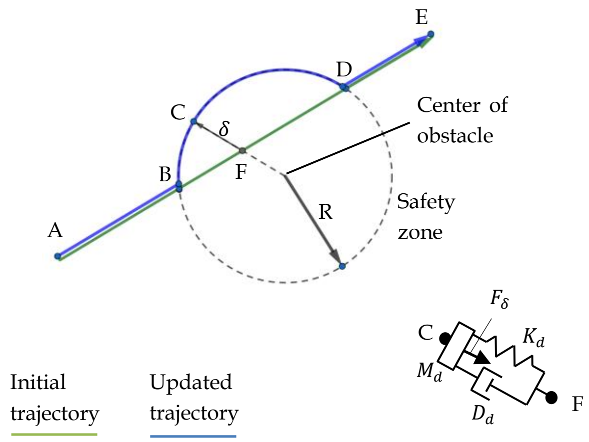

Fig. N. Obstacle avoidance by a quadrotor.

The location of drones and obstacles is defined by Vicon motion capture system as described in Section 2.3. Each quadrotor is aware of the position of local obstacles. Meanwhile, each obstacle has a safety zone around its center, which is defined as a sphere with radius R (Fig. N). For example, we assume that a quadrotor default trajectory goes from point A to point E as a straight line, see Fig. N for reference, crossing the safety region of the obstacle. In that case, the goal trajectory of the quadrotor is corrected, relatively to the obstacle pose. The new trajectory will go throught the points A-B-C-D-E, following the circumference, defining the obstacle boundary.

However, the defined obstacle avoidance method requires drones to move through the arc faster in comparison with a straight line trajectory. In addition, the quadrotors should perform sharp maneuvers being in the points B and D.

In order to make trajectories near obstacles more feasible (especially in points B and D) and more smooth we propose to use position based impedance control. We introduce mass-spring-damper model between point C and F, which is defined as $M_d\ddot{x} + D_d\dot{x} + K_d x = F_\delta(t)$ (Fig. N). Where M_d, D_d, and K_d is the desired dynamic coefficients. $F_\delta(t)$ is the virtual force which applied to the point C with a direction towards point F and is defined as $K_\delta \delta$. K_δ is the scaling coefficient and δ is the distance between points C and F, i.e. the desired jump into the safety zone. Above equation has to be solved with initial parameters which is defined using the state of the drone at the moment of crossing the border of the safety zone (initial velocity of the impedance model is equal to the projection of the drone velocity to the CF line). Solving the equation, we get the impedance correction term, which is used to update the drone goal position. As a result, the arc curvature is decreasing due to the dynamics of the impedance model. Therefore, the trajectory of drone in the vicinity of the obstacle becomes more smooth.

TODO: Create a real plot with trajectories.