

Occlusion-Safe Shared Micromanipulation in Vision-Constrained Environments

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Abstract—Vision-constrained teleoperation systems are vulnerable to occlusions, which can affect closed-loop control and compromise both performance and safety. We present an occlusion-safe shared-control framework that prevents robots from entering unobserved regions under fixed-camera monitoring. Our method combines Control Lyapunov Functions (CLFs) and High-Order Control Barrier Functions (HOCBFs) within a Quadratic Programming (QP) solver to enforce task goals and occlusion-avoidance constraints in real time. A human operator provides high-level commands through a 6-DoF haptic interface, while an autonomous safety layer ensures continuous visibility. To help the operator understand the system behavior, we deliver haptic feedback that signals proximity to occlusions and provide visual overlays supported by a virtual reality camera for improved scene understanding.

I. INTRODUCTION

Vision-based monitoring is widely used in robotic teleoperation and shared-control systems, but remains critically sensitive to occlusions. In microassembly or medical procedures, parts of the workspace may be hidden by obstacles or robots themselves, compromising visual tracking, control reliability, and safety [1]. Conventional methods address this by making vision systems more robust through predictive filtering or redundant coverage with additional cameras or virtual reconstructions. However, these approaches increase the operator's cognitive load and introduce new challenges for viewpoint selection and scene interpretation.

Recent research has explored proactive occlusion handling through viewpoint control and intelligent visual assistance: cooperative camera control and autonomous viewpoint planning have been developed to maximize task visibility [2]–[4], while VR-based interfaces and augmented reality overlays help users perceive hidden regions more intuitively [5]–[8].

Particularly at the microscale, maintaining reliable visibility of one or more microrobots is critical for successfully performing tasks under challenging microscale conditions. To address this, haptic shared control techniques have been used to enhance adaptability in perception-limited environments, allowing operators to interact with untethered microrobots while benefiting from autonomous safety constraints. Early works focused on direct haptic mapping for single agents [9], [10], evolving to collaborative shared-control schemes for micro-grippers and micro-swimmers [11]–[13]. However, these systems typically switch between discrete control modes rather than blending human and autonomous inputs continuously. Continuous constraint-based blending has been studied at larger scales for tasks such as robotic

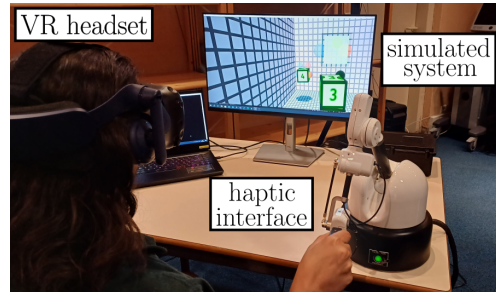


Fig. 1: System overview. A human operator performs a micromanipulation task in VR with kinesthetic feedback highlighting safety-critical occlusion constraints.

cutting and comfort-aware teleoperation [14], [15], and is starting to be adapted for microscale applications [16]–[18].

In this paper, we take a different approach: instead of passively coping with occlusions, we proactively prevent them by ensuring microrobots never enter occluded regions. We build on a recently proposed optimization-based micromanipulation system [19] and refine it within a shared-control paradigm. Specifically, our framework combines Control Lyapunov Functions (CLFs) for user-driven teleoperation with High-Order Control Barrier Functions (HOCBFs) for real-time occlusion avoidance, formulated as a Quadratic Program (QP). Operators steer microrobots via a 6-DoF haptic device and receive visuo-haptic feedback that conveys how the system enforces safety constraints, bridging the gap between 2D sensor projections and 3D micromanipulation.

The main contributions of this work are:

- A refined QP-based shared control framework, building on [19], that integrates CLFs and HOCBFs to teleoperate a pair of untethered electromagnetic microspheres while guaranteeing occlusion-free navigation under fixed-camera monitoring;
- Dual feedback modalities: (i) haptic cues and (ii) visual overlays, alerting the user to imminent occlusions;
- A Virtual Reality (VR) environment that renders the micromanipulation workspace and enables immersive free-flying camera control, exposing hidden regions and enhancing the operator's situational awareness.

II. OCCLUSION-SAFE MULTI-ROBOT CONTROL

A. Problem formulation

Consider a pair of magnetized microspheres (hereafter “microrobots”) inside a small-scale workspace, actuated by a controlled magnetic field and monitored by vision sensors, such as the BatMag electromagnetic system described in [20]. The setup uses $N_c = 9$ coils to generate magnetic fields and gradients, producing independent forces within the workspace, while 2 orthogonally placed cameras triangulate

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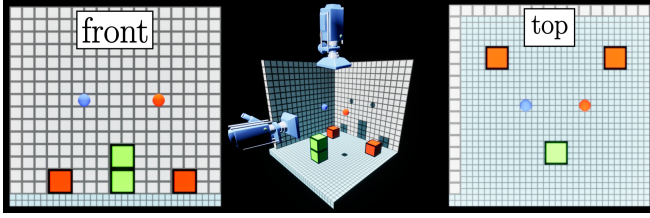


Fig. 2: Simulation scene. The orthogonal cameras (left: frontwards, right: top-down) in the original magnetic actuation system capture the current state of the workspace. A three-quarter view of the scene (middle) gives the user a more informative perception of the environment. Cameras in the middle view are shown closer to the workspace for the sake of clarity.

the microrobots' positions and velocities when they remain in overlapping fields of view. The workspace also contains N_o known small, cube-shaped components to be manipulated and assembled. Fig. 2 presents such an environment. Occlusions caused by these components or by self-alignment of the microrobots result in tracking loss and failed actuation.

The goal is to control the microrobots by modulating the magnetic field to generate the required forces, ensuring navigation while maintaining continuous visibility. Following the strategy in [19], this leads to the control objectives:

- (O1) steer the microrobots to a desired positions;
- (O2) avoid occlusions with objects and between microrobots;
- (O3) minimize the input control forces.

The next subsections formulate these objectives as an optimization-based control problem.

B. System modeling and control problem formulation

The magnetic field exerts forces $\mathbf{f}_{\mathcal{R},1}, \mathbf{f}_{\mathcal{R},2} \in \mathbb{R}^3$ at the microrobots positions $\mathbf{p}_1, \mathbf{p}_2 \in \mathbb{R}^3$, according to the model:

$$m_i(\ddot{\mathbf{p}}_i - \mathbf{g}) + c\mathbf{v}_i = \mathbf{f}_{\mathcal{R},i}, \quad i = 1, 2, \quad (1)$$

where $\mathbf{v}_i = \dot{\mathbf{p}}_i$, m_i is the mass, c the viscous coefficient of the medium, and $\mathbf{g}$ the gravity vector in $\mathcal{F}_W$ (the relative degree of $\mathbf{p}_i$ with respect to $\mathbf{f}_{\mathcal{R},i}$ is $\varrho = 2$).

Eq. (1) can be written as $\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}) + \mathbf{h}(\mathbf{x})\mathbf{u}$, an affine function with $\mathbf{x} = (\mathbf{p}_1, \mathbf{p}_2, \mathbf{v}_1, \mathbf{v}_2)^T = (\mathbf{p}, \mathbf{v})^T \in \mathbb{R}^{12}$ and $\mathbf{u} = (\mathbf{f}_{\mathcal{R},1}, \mathbf{f}_{\mathcal{R},2})^T \in \mathbb{R}^6$; $\mathbf{f} : \mathbb{R}^n \rightarrow \mathbb{R}^n$ and $\mathbf{h} : \mathbb{R}^n \rightarrow \mathbb{R}^{n \times m}$ are locally Lipschitz.

The control objectives (O1)–(O3) are enforced using a QP-CLF-CBF approach [21]. In detail, the QP minimizes a cost function subject to linear constraints derived from a CLF [22] to ensure *stability* (O1), and HOCBFs [23] to ensure *safety* (O2), while also minimizing the control effort (O3):

$$\mathbf{u}^*, \delta^* = \arg \min \mathcal{C}(\mathbf{u}) + \mu\delta^2 \quad (O3)$$

$$L_f V(\mathbf{x}) + L_h V(\mathbf{x})\mathbf{u} + \gamma(V(\mathbf{x})) \leq \delta \quad (O1) \quad (2)$$

$$\text{s.t. } L_f^2 B_{i,j,k}(\mathbf{x}) + L_h L_f B_{i,j,k}(\mathbf{x})\mathbf{u} + L_f \alpha_1(B_{i,j,k}(\mathbf{x})) + \alpha_2(\psi(\mathbf{x})) \geq 0 \quad (O2)$$

where, for $i = 1, 2, j = 1, \dots, N_o$ and $k = 1, 2$: δ is a slack variable to ensure feasibility between possible conflicting constraints, being $\mu \geq 0$ a penalizing factor; $\mathcal{C}(\mathbf{u})$ is a quadratic cost; L_f and L_h denote Lie derivatives along $\mathbf{f}$ and $\mathbf{h}$, α_1, α_2 ; and γ are extended class- $\mathcal{K}$ functions; and $\psi(\mathbf{x}) = \dot{B}(\mathbf{x}) + \alpha_1(B(\mathbf{x}))$. The input bounds are given

by $\mathbf{u}_{lb} \leq \mathbf{u} \leq \mathbf{u}_{ub}$. Note that (O2) appears as a HOCBF constraint of order 2, to reflect the position-dependent nature of the occlusion avoidance condition and the relative degree $\varrho = 2$, as explained in Sec. II-C.2. The functions $V(\mathbf{x})$, $B(\mathbf{x})$, $\mathcal{C}(\mathbf{u})$ are designed to satisfy the objectives, as follows.

C. Control objectives

1) **Objective O1 (Steer to the desired position)**: Driving the microrobots to reference positions $\mathbf{p}_r = (\mathbf{p}_{r,1}, \mathbf{p}_{r,2})^T$ and velocity $\mathbf{v}_r = (\mathbf{v}_{r,1}, \mathbf{v}_{r,2})^T$ requires regulating the system state to the reference $\mathbf{x}_r = (\mathbf{p}_r, \mathbf{v}_r)^T$, i.e., $\mathbf{x} \rightarrow \mathbf{x}_r$. This *stability* objective is enforced by defining the following CLF within the QP-based formulation (2):

$$V(\mathbf{x}) = \frac{1}{2}(\mathbf{x}_d - \mathbf{x})^T(\mathbf{x}_d - \mathbf{x}), \quad k_\gamma > 0 \quad (3)$$

$$\gamma(V(\mathbf{x})) = k_\gamma V(\mathbf{x})$$

where $\mathbf{x}_d$ is designed using a *backstepping technique* [24] to account for the relative degree $\varrho = 2$:

$$\mathbf{x}_d = \begin{bmatrix} \mathbf{p}_r \\ k_p(\mathbf{p}_r - \mathbf{p}) + k_v \mathbf{v}_r \end{bmatrix}, \quad k_p, k_v > 0. \quad (4)$$

2) **Objective O2 (Avoid occlusions)**: For each of the two cameras, occlusions must be avoided with static obstacles (or manipulable components) as well as between the microrobots themselves. This is achieved by ensuring that the projected trajectory of each microrobot in each camera's image plane does not intersect the projection of any occluding object. Fully enforcing the *safety* objective (O2) thus requires a separate HOCBF constraint, via the barrier function $B_{i,j,k}(\mathbf{x})$, for each microrobot (i) - occluder (j) - camera (k) combination, such that $B_{i,j,k}(\mathbf{x}) \geq 0$ guarantees no occlusion in the corresponding image plane. Since the camera-to-robot distance is much larger than the microrobots' motion scale, a parallel projection model is adopted. The projected distance between objects i and j in camera k is computed as

$$d_{i,j,k}(\mathbf{x}) = \|(I - \hat{\mathbf{c}}_k \hat{\mathbf{c}}_k^T)(\mathbf{p}_i - \mathbf{p}_j)\|, \quad (5)$$

where $\mathbf{p}_*(\mathbf{x})$ is the position of object $*$ and $\hat{\mathbf{c}}_k$ is the camera's principal axis. For conservative detection, each object is approximated by a bounding sphere, yielding circular projections. For (i, j, k) sets where (i) is further than (j) to (k) , hence potentially occluded, a barrier function is defined as

$$B_{i,j,k}(\mathbf{x}) = \|d_{i,j,k}(\mathbf{x})\|^2 - (r_i + r_j + \delta_{i,j,k})^2, \quad (6)$$

where r_* is the radius of the bounding sphere and $\delta_{i,j,k}$ is a user-defined safety margin. Each HOCBF is shaped with $\alpha_1(B_{i,j,k}) = k_{\alpha_1} B_{i,j,k}$ and $\alpha_2(\psi) = k_{\alpha_2} \psi^3$ ($k_{\alpha_1}, k_{\alpha_2} > 0$).

3) **Objective O3 (Minimize input control force)**: To minimize input control forces, we consider the norm of the microrobots' acceleration in the cost function $\mathcal{C}(\mathbf{u})$, i.e.,

$$\mathcal{C}(\mathbf{u}) = \frac{1}{2}\mathbf{u}^T \mathbf{H} \mathbf{u} + \mathbf{c}^T \mathbf{u} = \sum_{i=1}^2 \ddot{\mathbf{p}}_i^T \ddot{\mathbf{p}}_i = \sum_{i=1}^2 \frac{1}{m_i^2} \mathbf{u}_i^T \mathbf{u}_i + \frac{2}{m_i} (\mathbf{g} - \frac{c}{m_i} \mathbf{v}_i)^T \mathbf{u}_i + \|\mathbf{g} - \frac{c}{m_i} \mathbf{v}_i\|^2 \quad (7)$$

Once all the functions in (2) are defined, the optimization problem can be solved using a standard QP solver.

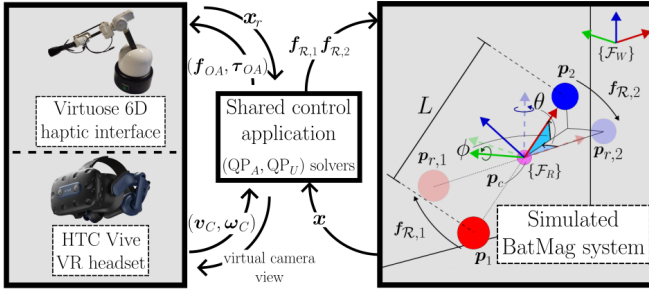


Fig. 3: System workflow. The user provides the reference state $\mathbf{x}_r$ through the haptic interface, corresponding to a reference microrobots formation $F_d = \langle \mathbf{p}_c, \phi, \theta, L \rangle$, and the simulated environment returns the current state $\mathbf{x}$. Our control framework computes, through QP_A and QP_U : i) the optimal forces $\mathbf{f}_{R,1-2}$, actuating the microrobots from positions $\mathbf{p}_{1-2}$; ii) the visuo-haptic sensory feedback provided to the user.

III. SHARED CONTROL FRAMEWORK

A. Shared Control Architecture

The proposed shared control setup consists of the following three main components (Fig. 1):

Virtual environment. A detailed simulation of the BatMag system is implemented in Unreal Engine. The built-in physics engine simulates the microrobots as rigid spheres subject to bounded forces.

VR headset. Unreal’s native VR rendering is paired with an HTC Vive headset to immerse the user in the simulated workspace. The headset’s tracking system maps the operator’s head motion to a free-flying camera motion $(\mathbf{v}_C, \omega_C)$ in the virtual scene, allowing intuitive first-person visualization of the micromanipulation task from any viewpoint.

Haptic interface. A Virtuose 6D (Haption, France) measures the position and orientation of an end-effector in real time; its handle includes a pinchable claw at the fingertip. The device provides full 6D force and torque feedback.

B. Teleoperated Micromanipulation

1) *Micromanipulation task:* The micromanipulation task involves steering the microrobots to collaboratively grasp, transport, and assemble small components. Fig. 4 illustrates a simple microassembly scenario (see also [25]).

2) *Teleoperation strategy:* The QP-based controller (2) is operated in a shared control mode, combining user input and autonomous corrections. As shown in Fig. 3, the user sets the desired reference state $\mathbf{x}_r = (\mathbf{p}_r, \mathbf{v}_r)^T$ for the stability objective (O1) by controlling a virtual formation $F_d = \langle \mathbf{p}_c, \phi, \theta, L \rangle$. Here, $\mathbf{p}_c = \frac{1}{2}(\mathbf{p}_1 + \mathbf{p}_2)$ is the formation centroid, θ and ϕ define the orientation of the inter-robot segment, and L its length, set by pinching the claw.

This yields the microrobots’ reference state, $\mathbf{p}_{r,i} = \mathbf{p}_c \pm \frac{L}{2}(\cos \phi \cos \theta, \cos \phi \sin \theta, \sin \phi)^T$ and $\mathbf{v}_{r,i}$ similarly, for $i = 1, 2$, to be used in (4) to achieve (O1).

C. Visuo-Haptic Sensory Feedback

For the considered setup, avoiding occlusions is critical: if a microrobot becomes undetectable due to occlusion, its state may be difficult to reconstruct, leading to failure of the control action and task interruption. Therefore, the

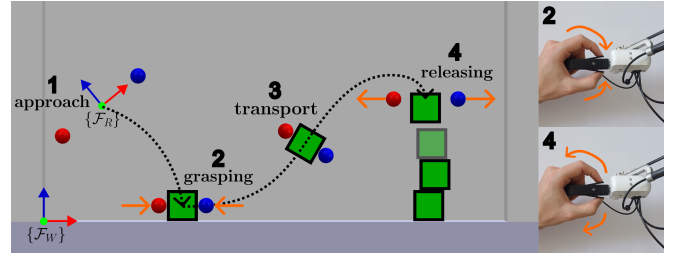


Fig. 4: Micromanipulation task: microrobots navigation towards the object (step 1); grasping manoeuvre by positioning around opposite sides of the target object and approaching towards each other (step 2); object transportation while kept it secured (step 3); object release at the target location by moving away from each other (step 4).

occlusion avoidance objective (O2) must always be enforced autonomously via the HOCBF constraint in (2).

However, understanding occlusions taking place in a 2D camera plane while performing a 3D manipulation task in a particularly mentally challenging task. To enhance the operator’s situational awareness and clarify deviations from the commanded trajectory, we complement the QP that generates the autonomous control action (QP_A) with an additional user-focused QP, denoted QP_U . Its purpose is to isolate the occlusion avoidance contribution and generate a feedback signal that can be rendered haptically or visually, indicating how this constraint influences the robot’s motion.

1) *Haptic feedback for occlusion avoidance:* In the haptic mode, QP_U solves for the same occlusion avoidance constraint as in QP_A , but based on the user’s location, producing a force–torque pair $(\mathbf{f}_{OA}, \tau_{OA})$. This is rendered in real time through the haptic interface, guiding the operator away from occluded areas, thus conveying how the system protects visibility while the user steers the microrobots.

2) *Visual feedback for occlusion avoidance:* The same information can be displayed visually. The occlusion avoidance force component of the robot motion, isolated from QP_A or equivalently computed by QP_U , is shown as a directional arrow anchored at each microrobot. Its support vector is computed as $\frac{\|\mathbf{u}_{occ}\|}{\|\mathbf{u}_{tlp}\| + \|\mathbf{u}_{occ}\|} \frac{\mathbf{u}}{u_{ub}} l_{max}$, where $\mathbf{u}_{tlp}$ and $\mathbf{u}_{occ}$ are the teleoperation and occlusion avoidance components, u_{ub} is the maximum input limit, and l_{max} is the arrow length scale. This visual cue helps the operator understand why the robot’s actual trajectory may differ from the direct teleoperation input. Fig. 5 displays a typical scene-crossing motion, where the user passes through an occluded area.

D. Preliminary experiment

A set of experimental conditions is proposed to test the different feedback typologies. A human operator is instructed to manipulate objects in the environment displayed in Fig. 2. To improve user agency, different shared occlusion avoidance typologies are tested on the user.

The autonomous occlusion avoidance of the robots can be supported by haptic feedback, visual cues extracted from QP_A or QP_U , or not at all. The user can monitor the scene using the original dual-camera set-up, a 3D reconstruction, or a VR headset, serving as a comparative baseline to evaluate the efficiency of the different occlusion avoidance strategies.

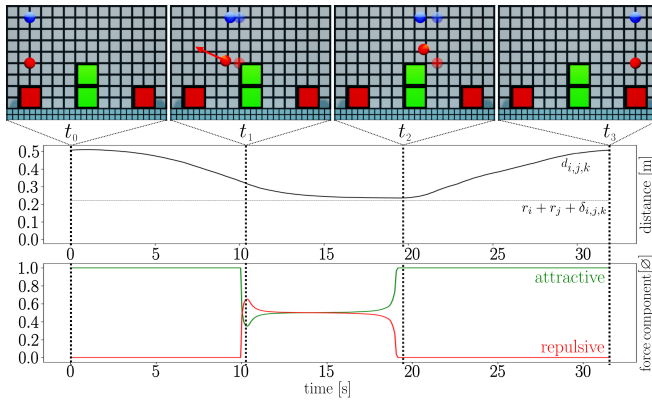


Fig. 5: Occlusion avoidance process. An operator (transparent) drives the robots (solid) from left to right; the red reference passes behind obstacles in the camera plane. At t_1 , the occlusion avoidance activates, pushing it up while attraction maintains forward motion. At t_2 , after clearing the obstacle, the constraint deactivates, leaving only teleoperation. Only the red robot's state is shown for clarity.

Initial (non-standardized) tests of micromanipulation in the proposed framework display encouraging results. Both visuo-haptic feedback typologies improve the overall task performance, with users needing a reduced amount of time to complete it. Participants appear to be more efficient at planning their trajectory or adapting it on the fly, with reduced distance covered by the microrobots. Subjectively, participants also mention the robot paths to be at times "confusing" without additional feedback, while reporting that the visual cues serve as an effective support to clarify the system's intention. A user study still needs to be conducted to confirm these initial results at a statistically relevant scale.

IV. CONCLUSION

We presented an occlusion-safe shared-control framework for vision-constrained microrobotic teleoperation that integrates CLFs and HOCBFs within a QP solver. By combining real-time haptic feedback and dynamic visual overlays in a VR environment, our method enforces task objectives while autonomously preventing occlusions. In a simulated microassembly task, users achieved a reduced task duration and more efficient trajectories compared to vision-only or fully autonomous baselines, reporting improved situational awareness. Despite these promising results, our evaluation remains limited to paired microspheres under fixed-camera monitoring, and haptic cues are restricted to force feedback alone. In the future, we will deploy the framework on a physical BatMag platform, addressing sensor noise and actuation delays, and explore adaptive safety margins and richer haptic textures to generalize across larger teams and dynamic environments.

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