A Collaborative Robot with Magnetic Perception

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***Abstract*—Safe and efficient human-robot collaboration remains a key challenge for deploying collaborative robots in industrial settings. While artificial vision is commonly used to provide robots with situational awareness, it often faces limitations due to occlusions, varying lighting conditions, and privacy concerns. This work introduces a novel approach for real-time, occlusion-free operator detection using magnetic field sensing. By mounting a magnetic tracking system on the end-effector of a robotic manipulator, our method reliably detects a passive magnetic marker worn or held by the operator. This enables dynamic adjustment of the robot's motion in response to user intent. Experimental results demonstrate the system's effectiveness in performing collision avoidance and contactless guidance, underscoring the potential of magnetic sensing to improve human-robot interaction across a wide range of environments.**

I. Introduction

Collaborative robots are increasingly being deployed in industrial and service environments, where they are required to operate safely in close proximity to humans. However, human movements are typically quicker and less predictable than those of robots, making collision-free interaction particularly challenging. Consequently, much of the existing research has shifted from solely preventing collisions to detecting, managing, and mitigating them when they occur [1], [2]. Nonetheless, in many applications, accurately tracking human motion and anticipating potential collisions remain critical for enabling safe, contactless human-robot collaboration.

To facilitate this, artificial vision systems are widely used to map the environment and identify users and obstacles [3]. Although effective, these systems suffer from several drawbacks, including susceptibility to occlusions, variations in lighting conditions, data privacy concerns, and compromises between latency and data throughput [3].

To overcome these limitations, we propose a novel sensing approach for enhancing human-robot interaction. Inspired by the proven success of magnetic tracking in medical and wearable robotics [4], we envisioned a robotic manipulator system that incorporates magnetic field sensing for collaborative applications (Fig. 1). In our system, the human operator wears or holds a passive magnetic marker, whose field is captured by a sensor array mounted on the robot's end-effector. A lightweight computational algorithm estimates the spatial position of the marker relative to the robot, enabling real-time awareness of the user's location—and potentially their intent. Our findings demonstrate the viability of magnetic tracking as a robust, occlusion-free alternative for enhancing human-robot collaboration, and they open new directions for integrating this sensing modality into robotic systems.

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II. Methods

A Franka Emika FR3 end-effector was fitted with a custom frame housing four digital magnetometers. Data from these sensors were collected and transmitted to a host PC managing the robot control in ROS.

We developed and validated a magnet detector capable of estimating the position of a permanent magnet using nonlinear optimization [5].

We implemented two motion generators on the host PC in C++, which processes magnet position information $\boldsymbol{r}_{dm}$ from the tracking algorithm to compute a desired velocity $\boldsymbol{v}_d$ for the robot's end-effector. The implemented motion generation strategies are Collision Avoidance (CA) and contactless Guidance (G). CA provides a velocity command that is inversely proportional to its distance from the detected magnet. Instead, in G, the velocity output is assigned to maintain a prescribed distance between a moving magnet and the end-effector.

In detail, we implemented the CA motion generator as a velocity-based repulsive vector field, which activates only when the distance between the magnet and the sensor array is less than a prescribed distance d_A. Denoting v_{max} as the robot's maximum allowable speed, the computed reference velocity is directed along the vector from the magnet to the detector, $\boldsymbol{r}_{dm}$, as described by the following equation:

$$\boldsymbol{v}_r = \boldsymbol{r}_{dm}\, v_{max} \exp\left(-\varpi \frac{\|\boldsymbol{r}_{dm}\|}{d_A}\right) \tag{1}$$

where $\boldsymbol{r}_{dm} = \boldsymbol{r}_{dm}/\|\boldsymbol{r}_{dm}\|$, and $\varpi \in \mathbb{R}$ is a decay factor that determines the rate at which the repulsive field weakens as the distance increases.

For the G motion generator, by defining a virtual reference point $\boldsymbol{r}_r$ fixed relative to the detector and by defining its distance vector from the magnet as $\boldsymbol{r}_{mr} = \boldsymbol{r}_m - \boldsymbol{r}_r$, we implemented the following velocity mapping:

$$\boldsymbol{v}_r = \frac{3\boldsymbol{r}_{mr}}{d_G} v_{max}\,. \tag{2}$$

Such a velocity mapping is computed within a prescribed distance from the magnet, i.e., when $\|\boldsymbol{r}_{mr}\| < d_G$. Here, the scaling factor $3/d_G$ was defined to avoid robot speed saturation and was determined through preliminary testing. The goal of such a motion generator is to ensure that the robot end-effector starts to follow the magnet only within a certain distance and

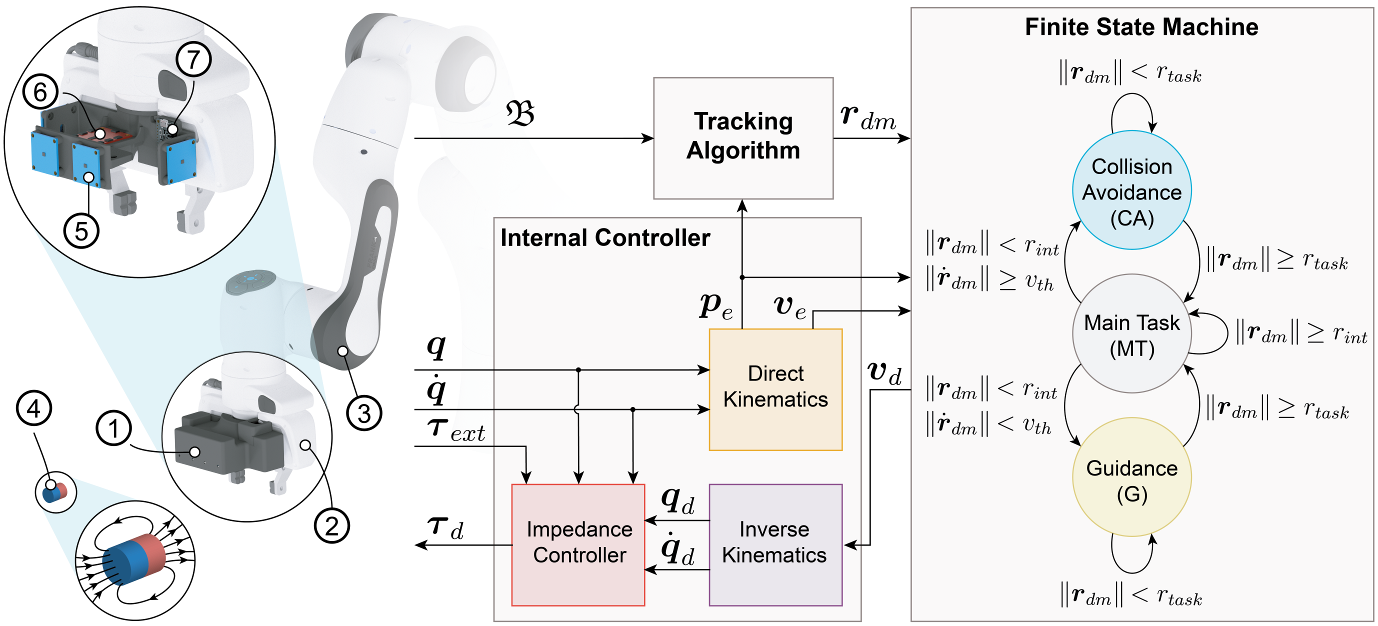

Fig. 1. The system comprises a robotic manipulator (3) with a magnetic tracking system (1) at the end-effector (2) used to track a magnet (4) in its proximity. The magnetic tracking system consists of four 3-axis magnetic sensors (5) connected through an I2C multiplexer (6) to a microcontroller (7). Motion generators are developed based on the robot's internal sensor data (joint positions and velocities) and the magnet spatial information, $\boldsymbol{r}_{dm}$. The developed motion generators are collision avoidance and guidance, which are selected by a finite state machine controller. The output of the motion generator is a desired end-effector velocity, which is imposed on the robot via an internal controller implementing inverse kinematics and joint impedance control.

guarantees a progressive slowdown of the end-effector speed when the reference point approaches the magnet.

A finite-state-machine (FSM) controller was also developed to automatically select the robot's behavior based on the user's proximity and velocity. By default, the robot follows a predefined trajectory to accomplish a given task (Main Task state, MT). When a magnet enters the interaction workspace, r_{int}, the robot becomes ready to switch motion strategies based on the magnet's velocity. If the velocity exceeds a threshold v_{th}, the FSM transitions to the CA state, where the robot follows a collision avoidance strategy to prevent contact with the magnet. Conversely, if the velocity remains below v_{th}, the FSM switches to the G state, allowing the robot to be controlled via contactless guidance. Once the FSM leaves the MT state, the selected strategy (CA or G) remains active until the magnet moves beyond a main task distance r_{task} (where

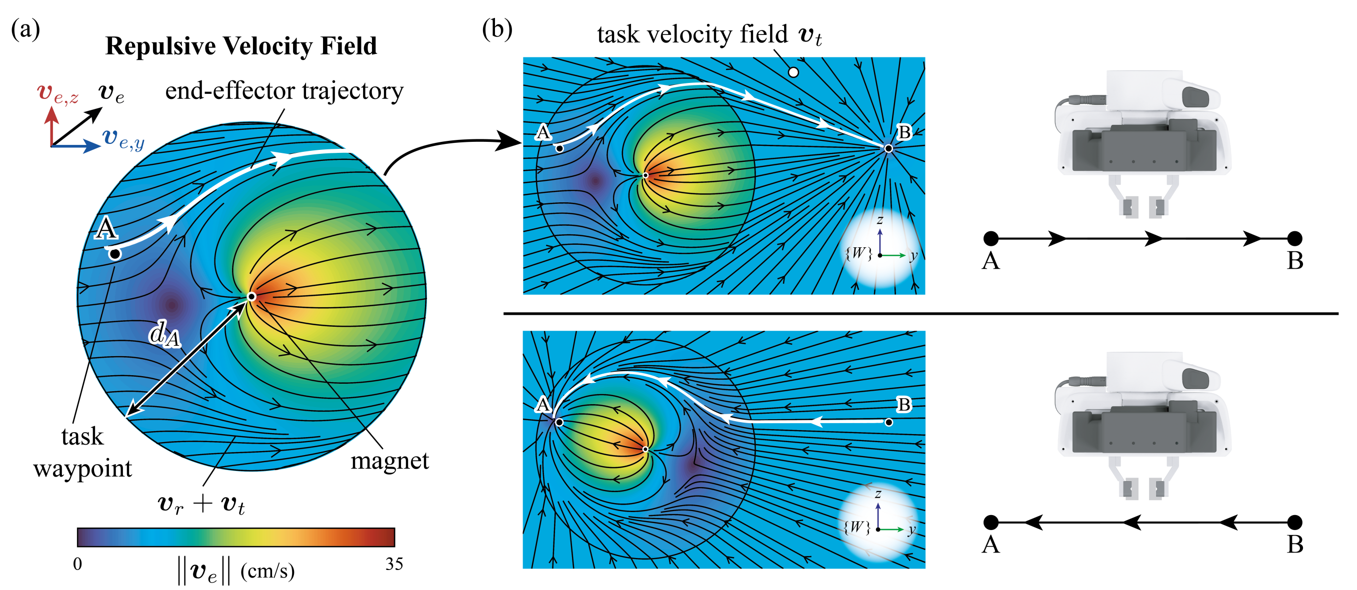

Fig. 2. (a) Compound repulsive and task velocity field simulated in MATLAB with $d_A = 30$ mm. The overlapping white line is the real end-effector trajectory recorded during the characterization experiment setting the same value of d_A. (b) Contour plots with overlapping field lines of the end-effector velocity field in the workspace region bringing from waypoint A to waypoint B (top panel) and from waypoint B to waypoint A (bot panel).

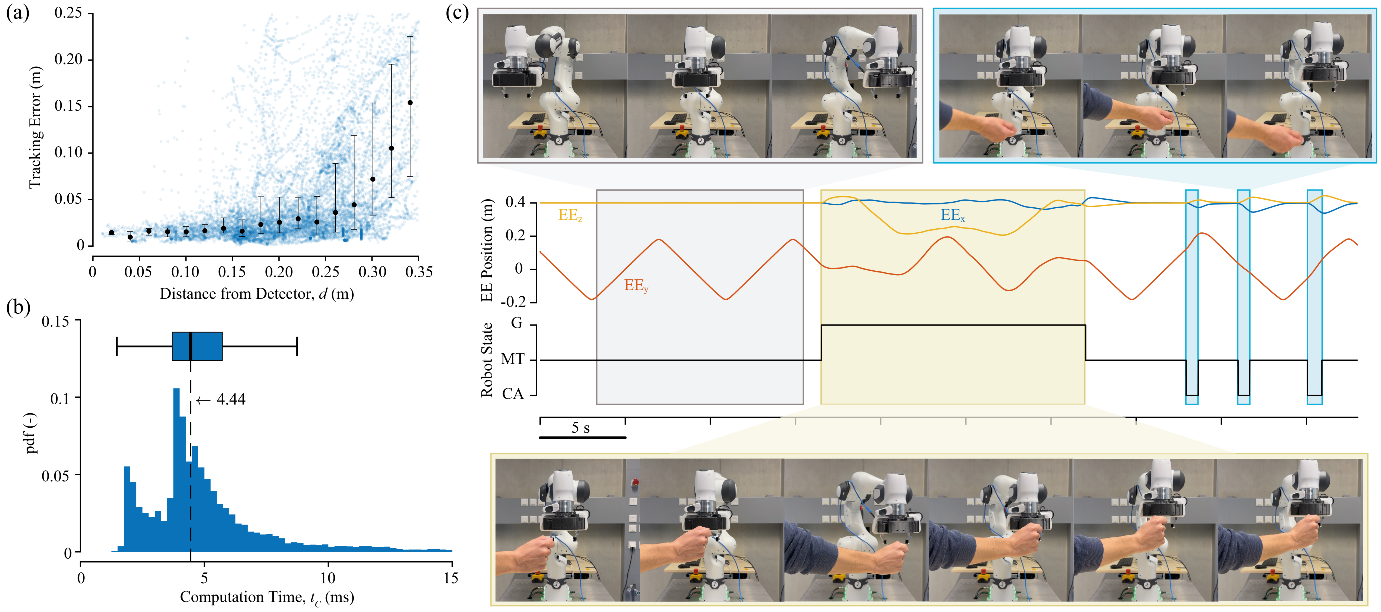

Fig. 3. (a) Position tracking error of the magnetic tracker vs. the magnet distance from the array. (b) Computation time of the tracking algorithm. (c) A representative illustration of the FSM controller in action: the user successfully triggered the desired motion modality while approaching the robot end-effector.

$r_{task} > r_{int}$), prompting the system to revert to the MT state.

III. Results

The spatial characterization of the tracking algorithm provided key insights into its accuracy and repeatability in localizing the magnet. The median tracking error remained below 2.5 cm for distances up to 20 cm, corresponding to a relative error of less than 13%. Additionally, the algorithm demonstrated efficient computational performance, with a maximum latency of 10 ms and a median of 4.44 ms.

A simulation and rendering of the exponential repulsive velocity field associated with the collision avoidance algorithm are presented in Fig. 2. By adjusting the parameters of the repulsive velocity field, the boundaries for collision avoidance can be made tighter or broader. The most critical parameter, the avoidance radius, d_A, set here to 30 cm, influences the end-effector trajectory (white line), causing it to follow a curved path around the magnet with a radius of curvature of approximately 18 cm (Fig. 2a). The parameter d_A defines the spherical region within which collision avoidance behavior is activated. Outside this region (i.e., when the distance from the magnet exceeds d_A), the robot end-effector is driven solely by the task velocity vector, $\boldsymbol{v}_t$, guiding it towards the target waypoint (B or A in Fig. 2b).

The implemented FSM enables the system to detect the user's hand holding an approaching magnet at different speeds and to switch between the desired motion modalities dynamically (Fig. 3).

IV. Discussions and Conclusion

Magnetic tracking offers a promising alternative to vision-based systems for human-robot interaction, with notable advantages in robustness, responsiveness, and adaptability. Unlike optical systems, which are often hindered by occlusions, varying lighting conditions, and bandwidth constraints, magnetic tracking enables continuous, line-of-sight-independent monitoring without imposing data transmission burdens [5]. While optical technologies can achieve comparable tracking latencies, magnetic systems provide a more favorable cost-to-complexity ratio: magnetometers and passive magnets are low-cost, compact, and easy to integrate, in contrast to the higher cost, size, and complexity of cameras, laser scanners, and optical markers.

In our implementation, magnetic tracking is combined with a finite-state machine for adaptive control, allowing the robot to dynamically switch between collision avoidance and guidance modes in response to the operator's behavior. This approach supports intuitive, fluid human-robot interaction, significantly enhancing the collaboration experience.

Future work will explore integrating magnetic tracking along the whole robotic structure, further improving safety and efficiency in human-robot coexistence.

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