Permanent Magnet-Assisted Omnidirectional Ball Drive

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Abstract—We present an omnidirectional ball wheel drive design that utilizes a permanent magnet as the drive roller to generate the contact force. Particularly interesting for novel human-mobile robot interaction scenarios where the users are expected to physically interact with many palm-sized robots, our design combines simplicity, low cost and compactness. We first detail our design and explain its key parameters. Then, we present our implementation and compare it with an omniwheel drive built with identical conditions and similar cost. Finally, we elaborate on main advantages and drawbacks of our design.

I. INTRODUCTION

In robotic locomotion, specialized scenarios are particularly interesting where one or more aspects of locomotion hardware are highlighted; such examples are affordability in swarm robotics due to the requirement of many robots; accuracy and repeatability in industrial robotics due to quality requirements; holonomicity in service robotics for maneuverability etc. Our focus is a novel human-robot interaction setting where we consider the following: Many palm-sized mobile robots (e.g. tens of robots) work simultaneously on a tabletop surface in everyday human environments (e.g. home, office or classroom). They not only convey information via their presence and actuation in the classical manner (i.e. pose, LEDs, sound etc.) but they are also intended to be often manipulated by the user as a tangible item and/or to receive haptic feedback for purposes such as kinesthetic learning: They are robots that can move and be moved.

This novel setting requires that our mobile robots have a small enough size to be entirely graspable by the user. When the robot is held, it must allow being externally driven and be able to give haptic feedback in any direction; therefore, it must be holonomic. The proposed design must be as low cost as possible (sacrificing precision if needed) and must fit inside a small enough volume using readily available parts so as to minimize custom machining need. We hypothesize that these requirements can be met rather efficiently using a ball wheel drive (i.e. ball drive, omnidirectional drive where each wheel is spherical with at least 2 DOF) due to its typical simplicity and potential compactness.

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Fig. 1: Overview of our design. The ball wheel with ferromagnetic core is driven by a permanent ring magnet that acts as the drive roller. The magnet temporarily magnetizes the wheel, exerting a pull force and generating the necessary normal force. The wheel thus acquires one driven and one free DOF, kinematically equivalent to an omniwheel.

freely around the horizontal axis orthogonal to the driven axis. It is well known that ideally, using at least 3 of any such ball wheel, a holonomic vehicle can be built.

[7] proposes a redundant scheme where each wheel is driven by two orthogonal rollers in a 3-wheel configuration. Each roller’s contact forces are actively regulated by pneumatic pistons to reduce wheel coating wear and increase obstacle robustness. [8] also features two drive rollers but with two spring-loaded sensor rollers opposite the drive rollers. With these, the wheel rotation is encoded and the drive roller-wheel slip is detected.

[9] [10] [11] [2] describe dynamically stable robots on a single ball wheel driven by (at least 2) omnidirectional/semi-omnidirectional wheels/rollers. [13] proposes a similar design where the single ball wheel is driven by two rollers, but the robot is enclosed in a spherical shell where the center of mass is located lower than the geometric center, ensuring that no dynamic balancing is needed to stay upright.

All above studies use rotating contact elements to drive the wheel, but there are alternative methods. [14] proposes a spherical induction motor scheme where a copper-over-iron spherical shell (acting as rotor) is omnidirectionally driven by multiple curved stators. [15] proposes driving a spherical wheel with an ultrasonic motor; this method has the potential for exceptional compactness and low cost.

In this study, we present a novel ball drive design (seen in Figure 1) that utilizes the magnetic force exerted by a permanent magnet to generate the normal force that ensures the friction force driving the ball wheel. Our design is aimed for maximum simplicity in order to lower the cost and ease
II. DESIGN

A. Overview & Key Principles

Our ball drive design, seen in Figure 1, has a permanent ring magnet located on the horizontal great circle of the wheel, acting as the drive roller. With the normal force generated by the magnetostatic interaction (i.e., pull) between the magnet and the wheel, the magnet can ideally drive the wheel around its axis of rotation thanks to the static contact friction while the wheel remains free to rotate around the orthogonal axis on the horizontal plane.

The placement ensures that the magnetostatic interaction stays isotropic regardless of the wheel’s or magnet’s orientations, assuming that the wheel’s core is magnetically isotropic in all directions and the magnet is magnetically isotropic around its rotation axis. Other important assumptions for isotropy are that the wheel core material is chosen appropriately and the wheel rotates slowly enough so that the parasitic forces due to the magnetic after-effect and induced eddy currents in the wheel are negligible. For example, it was empirically observed that these effects are significantly stronger with an AISI 440C stainless steel core wheel compared to an AISI 1010 carbon steel core wheel.

Utilizing the magnetostatic interaction to ensure the contact conditions eliminates the need for external elements that would normally ensure these conditions such as spring loaded passive rollers. In other words, the contact force mechanism is naturally embedded in the wheel and the drive roller (i.e., magnet). Given a wheel diameter, the normal force magnitude can be controlled in design by choosing the magnet size (analysis in the next section) and strength.

The ball wheel is loosely enclosed in a space defined by the drive roller and 4 ball transfer units: Above the wheel (bears the weight of the robot), opposite the drive roller and finally on the left and right of the wheel. As a design choice, the motor is not fixed on the frame and is left free to move along the plane perpendicular to the driven axis. The drive roller and the wheel are also free to move along this plane but are constrained by the frame and the ball transfers respectively: They are only allowed to move a very small plane but are constrained by the frame and the ball transfers move along the plane perpendicular to the driven axis. The choice, the motor is not fixed on the frame and is left free to move along the plane perpendicular to the driven axis.

A final consideration is the encoding of wheel rotation for dead-reckoning purposes, which is not trivial for a design such as ours. Two low-cost solutions in the literature are optical mouse sensors on wheels (such as the one in [14]) and rotary encoders on the motor shaft. Our solution is to use the absolute global localization method described in [15]. This method is based on decoding a printed structured microdot pattern on the ground with an onboard camera; although it is very low cost, it is robust against motion, works in real time and can ensure sub-mm accuracy. With this, we estimate the wheel velocities using the robot velocity \((v_x, v_y, \omega)\) with inverse kinematics.

B. Magnetostatic Wheel-Magnet Interaction Analysis

The magnetostatic interaction between the ball wheel and the magnet depends on the physical dimensions of both objects and is not trivial to predict. Given such dimensions, it is desirable to know where the ball will rest along the height of the magnet (if it rests at all) and how much force will be exerted on it. In order to determine these, the pull and shear forces on the wheel were calculated using COMSOL Multiphysics (Finite Element Analysis software) for fixed ball wheel dimensions and parametric magnet dimensions and position, as seen in Figure 2. The resulting shear forces were used to calculate the potential of the wheel in order to determine its resting position. Throughout the section, the wheel resting position (i.e., \(p_{wheel}\)) is given in percentages of the magnet height (i.e., \(h_{magnet}\)) to remain invariant to the magnet height parametrization: 0% corresponds to the upper edge, 50% corresponds to midway between two edges etc.

The results of the analysis, namely resting positions and pull forces, are given in Figures 4a and 5b respectively. Considering the resting positions in the parameter space, it can be seen that there exists a threshold below which the wheel rests at the center of the magnet (example in Figure 4a), requiring small enough \(h_{magnet}\) and large enough \(d_{magnet}\).
that F
\[\text{symmetric around the resting position. Finally, it is observed that pull}
\] such pairs of magnet dimensions, F
\[\text{increasing d}
\] magnet magnetization assumed to be μ
\[\text{magnet-wheel}
\] wheel rests at some position along the magnet height larger h
\[\text{magnet}
\] quickly move away from the center towards the edges with magnet rests against the frame instead of being supported by the motor shaft. These sources of friction move the dynamics of the system away from ideal conditions.

Fig. 3: Magnetostatic wheel-magnet interaction analysis results. Wheel core permeability assumed to be μ
\[\text{calibrated by measuring force exerted by real magnet.}
\] For all such pairs of magnet dimensions, F
\[\text{shown above) due to magnet’s symmetry.}
\] (not shown above)
\[\text{example in Figure 4b), but for other wheels and the overall geometry of the system.}
\] For this reason, we incorporate our own ball transfer units inside our frame by manufacturing simple enclosures for off-the-shelf bearing balls. Moreover, since the wheel-magnet assembly is not fixed onto the frame, the pull is observed to not be symmetric around the resting position region; it is desirable to have symmetric F
\[\text{weight of the robot and to enclose the ball wheels. At our scales (e.g. 10mm wheel diameter), it is very difficult to obtain off-the-shelf, low-cost and high-performance ball transfer units. For this reason, we incorporate our own ball transfer units inside our frame by manufacturing simple enclosures for off-the-shelf bearing balls. Moreover, since the wheel-magnet assembly is not fixed onto the frame, the pull is observed to not be symmetric around the resting position region; it is desirable to have symmetric F
\text{pull magnitude around the resting position, since the wheel will inevitably move a small amount along the magnet height due to inaccuracies during motions involving its free DOF in a multi-wheel configuration. In this region, we chose the smallest geometrically feasible pair of off-the-shelf dimensions that would ensure enough F
\text{which corresponds to d
\text{magnet} = 10\text{mm} and h\text{magnet} = 5\text{mm}.}
\]

C. Dynamics of Single Ball Drive

In our design, ball transfer units are used to support the weight of the robot and to enclose the ball wheels. At our scales (e.g. 10mm wheel diameter), it is very difficult to obtain off-the-shelf, low-cost and high-performance ball transfer units. For this reason, we incorporate our own ball transfer units inside our frame by manufacturing simple enclosures for off-the-shelf bearing balls. Moreover, since the wheel-magnet assembly is not fixed onto the frame, the pull is observed to not be symmetric around the resting position region; it is desirable to have symmetric F
\[\text{pull magnitude around the resting position, since the wheel will inevitably move a small amount along the magnet height due to inaccuracies during motions involving its free DOF in a multi-wheel configuration. In this region, we chose the smallest geometrically feasible pair of off-the-shelf dimensions that would ensure enough F
\text{which corresponds to d
\text{magnet} = 10\text{mm} and h\text{magnet} = 5\text{mm}.}
\]

In forward mode, with small enough torque (first case above), the system enters a degenerate state where the robot frame is only accelerated by the top ball transfer and magnet-frame contacts (i.e. by F
\[\text{magnet-wheel}
\] wheel-ground slip always occurs before wheel-magnet slip thanks to the magnetic pull force (backward mode torques indicated with negative values):
\[\text{wheel-magnet slips}
\] wheel-ground slips
\[\text{wheel-magnet slips}
\]
\[\text{wheel-ground slips}
\]
\[\text{wheel-ground slips}
\]
\[\text{wheel-ground slips}
\]

This analysis covers the dynamics of each wheel independently under assumptions such as the existence of 3 wheels in total and equal weight distribution per wheel. However, the dynamics of a given wheel depends also on the dynamics of other wheels and the overall geometry of the system. Moreover, external manipulation by users may affect the dynamics, and may require additional sensors to detect and handle correctly. These concerns are not considered in this study and will be addressed in the future.

\[\text{using components described in Section III P}_{\text{wheel}} = 1.232N, \mu_s = 0.37 \text{ (measured), } 
\]
\[\mu_s \text{ wheel-ball transfer } = 0.7 \text{ (assumed, depends on ground material).}
\]
III. IMPLEMENTATION

The proposed ball drive was implemented in the widely used 3-wheel configuration, as seen in Figure 6, the natural geometry of our design (i.e. motor on the side of wheel) allows such a compact placement of the components in this configuration. The frame (including ball transfer enclosures embedded within it) and motor shaft adapters for the magnets were manufactured using Fused Filament Fabrication (FFF) with Polylactic Acid (PLA). The frame has a hexagonal form (73mm width, 80mm end-to-end) enclosing all locomotion components and isolating them from the outside world except three 11mm-diameter holes on the bottom where the wheels contact the ground. The ground clearance is 0.8mm and the entire locomotion subsystem fits inside a height of 19mm inside the robot, measured from the ground.

Apart from the above, all components are off-the-shelf. This includes the ball transfer units which are simple Poly-tetrafluoroethylene (PTFE) balls enclosed in the frame. Two more were added to the bottom of each wheel to keep them from contacting the frame when the robot is picked up; they are not active during normal motion. The wheels are AISI 1010 carbon steel balls with a 1mm-thick Nitrile Butadiene Rubber (NBR) coating of Shore A 90 hardness. These and other components are listed in Table I with their typical cost.

The wheels are driven with a motion controller that tracks a command pose by determining the required robot velocity \((v_x, v_y, \omega)\) in a closed loop fashion (i.e. PID). Wheel velocities \((v_1, v_2, v_3)\) are then calculated from the required robot velocity (using inverse kinematics and the current global orientation of the robot) and are set in a calibrated open loop that takes into account the results of the analysis in Section II-C. This simple controller was observed to be adequate for the evaluation made in the following section, and will be improved in the future.

IV. COMPARATIVE EVALUATION

A. Experiment Design

In order to test the performance of our design against a baseline, we built an alternative version of our robot with omniwheels, seen in Figure 7, with the same geometry and kinematics except the wheel offset from center (28mm vs. 46.9mm). The same manufacturing methods and components were used except 50:1 gearbox motors instead of 30:1. Care was taken during frame manufacturing that both robots have roughly the same weight (178.9g vs. 178.1g). The 30mm-diameter omniwheels were custom manufactured due

![Figure 5: Dynamics of ball drive, side view. Normal, friction, gravity and magnetic pull forces denoted with N, F, G and P respectively. Torque denoted with T. Ball wheel, magnet, frame and ground (rigid bodies) denoted with w, m, f and g respectively. Different contact points on frame denoted with bs, bt (ball transfers), ft, fs and fb (surfaces acting as plain bearings). Forces acting on wheel, magnet and frame colored in red, blue and black respectively.](image)

![Figure 6: Ball drive implementation, size given in mm. Main body (on the left) rests bottom-side-up. Bottom “lid” opened (on the right) and two ball wheels removed from enclosures for better visibility of internals. In the center, camera lens aperture and 3 exposure LEDs used for localization are seen.](image)

![Table I: List of off-the-shelf components and their cost.](table)
to the lack of such a small size off-the-shelf: The rims were manufactured with FFF while the rollers (hard plastic core, 1mm-thick Shore A 85 hardness rubber-like exterior) were manufactured with Multi Jet Modeling (MJM) for 2.18E per roller. The same motion controller was used with appropriately calibrated coefficients in both robots.

Both robots were commanded to follow the square trajectory seen in Figure 8 with 150mm/s maximum linear velocity and π/4 0.067 rad/s maximum angular velocity. These commands were given on the corners of the trajectory when they are reached, i.e. a total of 4 times. The particular usage of global localization in the motion controller ensures that the goals are eventually reached, but the controller does not ensure tracking of real velocities and therefore fidelity to the ideal trajectory in a closed loop. 10 runs were done for each robot where pose data were collected at about 46.6Hz from the robot’s own global localization system. In this setup, the sources of significant systematic error are identified as:

- FFF and MJM tolerances, notably for magnet-shaft adapters, ball transfer housings and omniwheel rollers
- Ball wheel fabrication tolerances: Off-center core results in anisotropic moment of inertia and magnetic forces
- Variances of off-the-shelf motors, causing some wheels to consistently rotate more than others with same input

B. Results & Discussion

To compare the performances of the two robots, deviations from the ideal trajectory (defined as the accelerationless constant-velocity trajectory from one command pose to the next) were calculated for each sample, separately for $x$, $y$ and $\theta$. Typical motions of the robots can be seen in Figure 9 while the overall performances are compared in Table II. The results indicate that the omniwheel drive performed better in $x$ and $\theta$ while the difference in $y$ was not statistically discernible. However, when the mean deviations are compared with the trajectory lengths, it is seen that the deviations differ by 0.31%, 0.01% and 0.14% of the total trajectory length for $x$, $y$ and $\theta$ respectively. When the worst deviations from each of the 10 runs are considered, the deviations differ by 0.93%, 0.26% and 0.28% of the total trajectory length.

Additionally, the omniwheel drive was visually observed to vibrate significantly more compared to the ball drive, as predicted by the literature (this difference can be quantified in the future by an accelerometer on board the robot). As mentioned previously, the proposed ball drive design also tends to be more geometrically compact (both horizontally and vertically) compared to a kinematically equivalent omniwheel drive design. If the performance differences provided

#### Table II: Performance of both drives measured in deviation from ideal trajectory. In mean, all samples from all 10 runs were taken, $N = 8183$ for ball drive, $N = 7705$ for omniwheel drive. In worst, maximum deviation of each run was taken, $N = 10$ for both. Values given with ± one σ.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Measured quantity</th>
<th>Ball drive</th>
<th>O.w. drive</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>$x_{\text{sampled}} - x_{\text{ideal}}$ (mm)</td>
<td>11.1 ± 11.3</td>
<td>7.53 ± 8.26</td>
</tr>
<tr>
<td></td>
<td>$y_{\text{sampled}} - y_{\text{ideal}}$ (mm)</td>
<td>6.52 ± 7.07</td>
<td>6.66 ± 7.80</td>
</tr>
<tr>
<td></td>
<td>$\theta_{\text{sampled}} - \theta_{\text{ideal}}$ (deg)</td>
<td>5.40 ± 3.80</td>
<td>4.40 ± 3.14</td>
</tr>
</tbody>
</table>

| Worst  | $x_{\text{sampled}} - x_{\text{ideal}}$ (mm) | 44.6 ± 4.48 | 33.3 ± 6.31 |
|        | $y_{\text{sampled}} - y_{\text{ideal}}$ (mm) | 30.8 ± 7.44 | 34.0 ± 4.84 |
|        | $\theta_{\text{sampled}} - \theta_{\text{ideal}}$ (deg) | 14.9 ± 2.00 | 12.9 ± 1.94 |
above (and other shortcomings) can be tolerated in a given application, the ball drive design can be preferred over the traditional omniwheels for these (and other) added benefits.

V. CONCLUSIONS

In this study we presented a novel element for omnidirectional ball drives, namely permanent magnet assistance, that will potentially lower cost and increase miniaturizability. The advantages of our design include:

- Almost fully made of low cost off-the-shelf components
- Naturally compact geometry enables it to fit inside a palm-sized robot with such components
- Less vibrations and smoother motion compared to omniwheels
- Minimum mechanical components that must be exposed to the outside world are smaller and simpler compared to omniwheels (rubber sphere segments vs. omniwheel rim ends and rollers), potentially reducing distractions and cognitive load in (mainly younger) users
- Equivalent control on drive roller-wheel contact force with simpler elements, compared to traditional passive mechanisms in other ball drive designs (e.g. spring-loaded passive roller, drive roller deformation)
- By virtue of magnetic force preservation, magnet-wheel assembly can be left unmounted from the frame, leading to a simple user interaction robustness mechanism

However, it also comes with certain drawbacks:

- Not suitable for high-precision applications
- Requires robot to be lightweight enough due to low load bearing capabilities of simple ball transfer units
- Requires robot to be small enough in size; larger robots would require potentially too large and dangerous magnets and too heavy ball wheels
- Requires flat enough surface (e.g. tabletop) to run on due to low ground clearance
- Encoding ball wheels is not trivial
- More complicated dynamics compared to omniwheels
- Produces more audible noise compared to omniwheels due to the frame acting as plain bearing for the magnet
- Performance may potentially degrade over time due to accumulation of foreign materials in the system during normal use

We believe that our omnidirectional drive design, being affordable but still robust against human manipulation, is particularly useful for human-robot interaction settings where many mobile robots capable of haptic interaction on some level are present. In the future, dynamics of our drive will be studied as a complete system in the presence of user manipulation in order to develop a motion/haptic feedback controller, with additional sensors if necessary. Finally, focused user studies will be done to evaluate further qualities of our design such as user friendliness and haptic fidelity.

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References