Coaxial Multi-Channel Rotary Transmission Device

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Abstract We present a novel coaxial multi-channel rotary transmission that provides multiple continuous rotary channels along a shared axis, enabling compact multi-axis actuation. The proposed design minimizes mechanical footprint while preserving motion independence and low driving inertia. Its modular architecture supports scalable, high-density actuation with simplified assembly. We introduce the transmission concept, describe a prototype implementation, and report experimental results validating the systems performance.

1 Introduction

Efficient transmission of rotary motion is fundamental in robotics, aerospace, and industrial automation [15]. Modern systems increasingly require compact mechanisms capable of transmitting multiple independent motions while minimizing space and mechanical complexity [4, 19]. Traditional solutions

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typically allocate a dedicated transmission path for each degree of freedom, resulting in bulky assemblies composed of multiple shafts, gearboxes, or drive chains [12, 10].

This paper introduces a *Coaxial Multi-Channel Rotary Transmission System*, a compact mechanism capable of transmitting multiple independent continuous rotary motions along a shared axis (see accompanying video[1]). As illustrated in Fig. 1, each independent motion path, referred to as a *rotary channel*, is implemented using concentric hollow shafts, allowing several channels to coexist within the same mechanical axis. Such a configuration is particularly suitable for applications where space, symmetry, or enclosure integrity are critical. Multiple rotary drives can be transmitted through a single opening, which is advantageous for sealed systems such as underwater or space robots [18, 7]. To demonstrate its feasibility, the transmission is integrated into a compact omnidirectional ball robot. The proposed architecture may also be of interest for robotic manipulators, aerospace actuators, and compact industrial mechanisms, where multiple independent rotary drives are desirable. The remainder of this paper reviews related work, presents the transmission architecture, describes a robotic implementation, and reports experimental validation.

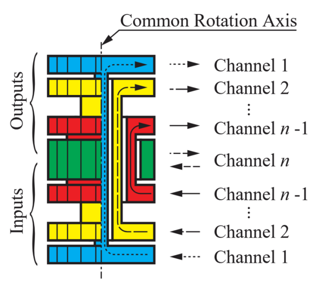


Fig. 1: Conceptual cutaway of nested rotary channel architecture.

2 Related Works

Concentric or nested shafts are a common solution for transmitting multiple motions along a shared axis. These systems use hollow shafts placed within one another, each driven by a separate actuator [11, 17]. Examples include concentric tube robots used in surgical robotics [6]. Industrial actuators such as hollow-shaft drives and modular actuator systems also rely on this principle [11, 1], while ultrasonic actuators with hollow cores allow signal routing

[1] https://www.youtube.com/watch?v=beV5KqHN_F4

through the actuator axis [20]. However, increasing the number of channels often leads to higher friction, mechanical complexity, and integration challenges [8, 14].

Gear-based multi-axis transmissions such as differential gear assemblies and planetary gearboxes are also widely used in robotic mechanisms [2, 5]. These systems provide compact and robust torque transmission and are commonly found in robotic limbs and articulated structures. For instance, Crispel et al. [5] proposed a Wolfrom-based gearbox that reduces actuator volume while maintaining output torque. However, such architectures typically introduce kinematic coupling between channels, making independent motion control more difficult. Although differential mechanisms can combine or subtract motions, they do not provide fully decoupled multi-channel transmission along the same axis.

Finally, compact actuation systems are also required in mobile and balance-sensitive[2] robots. For example, the neck mechanism of the Miroki robot developed by Enchanted Tools [13] illustrates the need for highly integrated actuation within constrained volumes. Other examples include modular hollow joints [16], integrated drive-arm assemblies [9], and rotary slip-ring solutions for multi-axis robots [3]. These developments highlight the ongoing demand for compact, modular transmission architectures capable of supporting independent rotary channels.

3 Coaxial Multi-Channel Rotary Transmission Concept

The proposed transmission integrates multiple independent rotary channels in a single coaxial structure. Each channel provides unlimited rotation and is implemented using nested hollow cylindrical shafts. Although the architecture can theoretically support many channels, the practical number is constrained by factors such as system diameter, structural rigidity, and bearing integration. Each rotary channel connects an input gear to a corresponding output gear through a dedicated hollow shaft. The shafts are arranged concentrically, forming a compact and modular assembly simplifying construction and maintenance. This section illustrates a four-channel configuration as a representative implementation. The system transmits four independent rotary motions along the same axis and demonstrates the scalability of the concept. The mechanical layout is shown in Fig. 2. The sectional view highlights the four rotary channels, which are color-coded and mechanically isolated except for minimal contact through thrust bearings. For clarity, a gap separates the input and output gears, which can also allow the transmission to pass through structural walls or enclosures.

[2] Where mass symmetry is critical for stability.

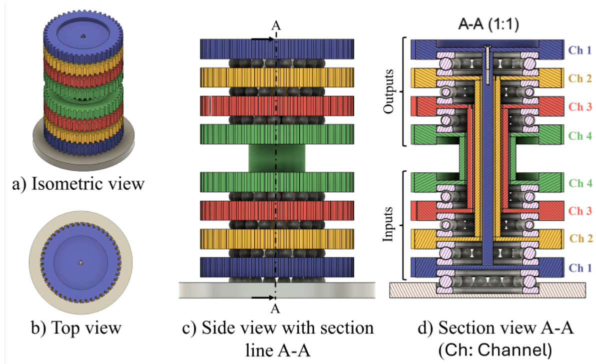


Fig. 2: Technical drawing and sectional view of the 4-channel coaxial rotary system.

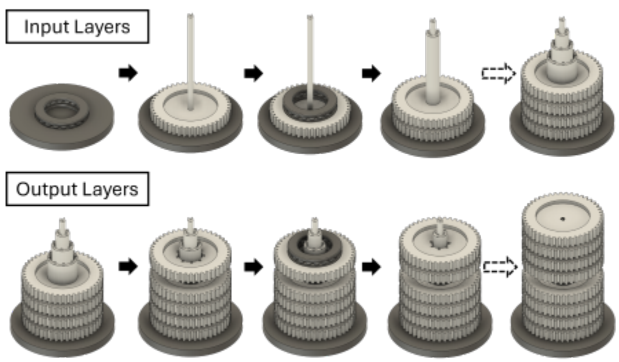


Fig. 3: Assembly steps for 4-channel example.

Assembly is illustrated in Fig. 3. Each rotary channel consists of an input and output gear connected through a hollow shaft, with shaft length depending on the output position. At the distal end, a keyed or dowel interface transmits torque, and the outermost gear is secured with a central screw that compresses the thrust bearings to eliminate axial backlash. And, although the innermost shaft is relatively thin, axial loads are supported by the thrust bearing system and the outermost shaft, maintaining structural stiffness. Torque capacity is primarily set by the dowel diameter and hollow shaft wall thickness; in our prototypes (Section 5), 2 mm steel dowels provide sufficient strength. The architecture can be scaled by adding or removing channels. However, each additional hollow shaft increases the overall diameter, which must be considered in space-constrained applications. Finally, although spur gears are used in the prototype, the design can accommodate other gear types such as bevel gears or custom gear ratios.

4 Implementation for a Ball Bot

To validate the proposed transmission, a 3-channel version was implemented in an omnidirectional ball robot designed to drive a non-rigid ball. Similar to robots such as Miroki [13], this platform requires a compact and balanced actuation system.

4.1 Mechanical Implementation

The implemented mechanism, shown in Fig. 4, includes three input gears (blue, yellow, red) and two output gear stages (red and yellow), with the red channel being merged into one gear. Compared with the generic four-channel architecture, this implementation removes the axial gap between gear stages, reducing height and improving structural strength. Three continuous-rotation servomotors are mounted at the input stage (Fig. 5). Each motor actuates a corresponding rotary channel. At the output stage, a header distributes motion to the omni-wheel pairs. The first channel (red) drives a first pair of omni-wheels, while the second channel (yellow) surrounds it and drives a second pair of omni-wheels. These two channels enable planar motion of the robot. The third inner channel (blue) passes through the transmission and controls rotation around the vertical axis.

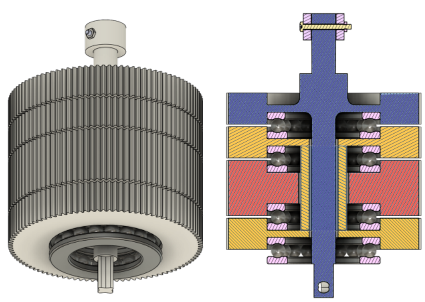


Fig. 4: Transmission system integrated into an omnidirectional ball bot (3-channel).

4.2 Ball Bot Kinematics and Control

Although the transmission channels are mechanically independent, the rotating chassis introduces motion coupling. When the robot rotates, the motor

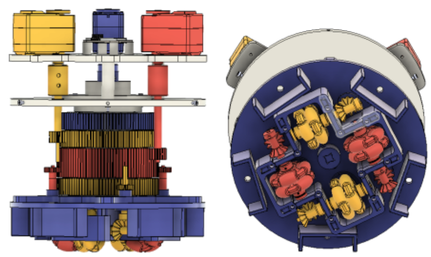


Fig. 5: Mechanical integration of the coaxial transmission (ball omitted for clarity).

assemblies rotate with the frame, generating parasitic wheel velocities. This effect is expressed in the robots motion model (Equation 1), which relates the motor input speeds (w_1, w_2, w_3) to the linear and angular velocities of the robot. We define the following variables:

r_W: Radius of the omni-wheels.
w_i: Rotational speed of servomotor i.
α_{ab}: Rotational speed ratio from component a to component b.
$\dot{x}$: Linear velocity of the robot along its primary axis.
$\dot{y}$: Linear velocity of the robot along its secondary axis.
$\dot{\theta}$: Rotational velocity of the robot around its vertical axis.

We also define the following reference elements:

c_i: Central gear driven by servomotor w_i, transmitting motion to output element o_i.
o_i: Output shaft associated with rotary channel i, which drives an omni-wheel.

So our forward kinematic model can be written:

$$\begin{cases} \dot{x} = r_w \left(\alpha_{c_2 o_2} \left(\alpha_{w_2 c_2} w_2 + \dot{\theta} \right) \right) \\ \dot{y} = r_w \left(\alpha_{c_3 o_3} \left(\alpha_{w_3 c_3} w_3 + \dot{\theta} \right) \right) \\ \dot{\theta} = \alpha_{w_1 c_1} w_1 \end{cases} \tag{1}$$

This formulation can also be expressed using a matrix equation (Equation 2).

$$\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{pmatrix} = A \begin{pmatrix} w_1 \\ w_2 \\ w_3 \end{pmatrix}, \quad A = \begin{pmatrix} r_w \alpha_{c_2 o_2} \alpha_{w_1 c_1} & r_w \alpha_{c_2 o_2} \alpha_{w_2 c_2} & 0 \\ r_w \alpha_{c_3 o_3} \alpha_{w_1 c_1} & 0 & r_w \alpha_{c_3 o_3} \alpha_{w_3 c_3} \\ \alpha_{w_1 c_1} & 0 & 0 \end{pmatrix} \tag{2}$$

To ensure that the system allows for independent control of all three degrees of freedom, we require the Jacobian matrix A in Equation 2 to be invertible.

This condition guarantees that any desired velocity vector $(\dot{x}, \dot{y}, \dot{\theta})$ can be uniquely mapped to a corresponding set of motor commands (w_1, w_2, w_3). The determinant of A is given by:

$$|A| = r_w^2 \cdot \alpha_{c_2o_2} \cdot \alpha_{w_2c_2} \cdot \alpha_{c_3o_3} \cdot \alpha_{w_3c_3} \cdot \alpha_{w_1c_1} \tag{3}$$

Since all gear ratios α_{ab} and the omni-wheel radius r_w are strictly positive by design, the determinant $|A|$ is always non-zero, which guarantees A being non-singular. The inverse matrix A^{-1} is configuration independent and can be calculated in closed form as follows, which maps desired velocity to motor velocities as shown in Fig. 6.

$$A^{-1} = \begin{pmatrix} 0 & 0 & \alpha_{w_1c_1}^{-1} \\ (r_w\alpha_{c_2o_2}\alpha_{w_2c_2})^{-1} & 0 & -\alpha_{w_2c_2}^{-1} \\ 0 & (r_w\alpha_{c_3o_3}\alpha_{w_3c_3})^{-1} & -\alpha_{w_3c_3}^{-1} \end{pmatrix} \tag{4}$$

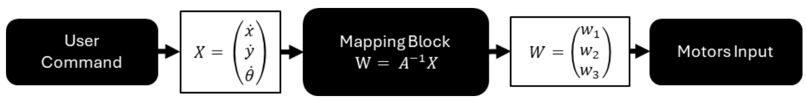


Fig. 6: Block diagram of logic for compensating rotation-induced coupling effects.

5 Performance Evaluation

The transmission system was implemented and tested on two ball robot prototypes to evaluate its functionality.

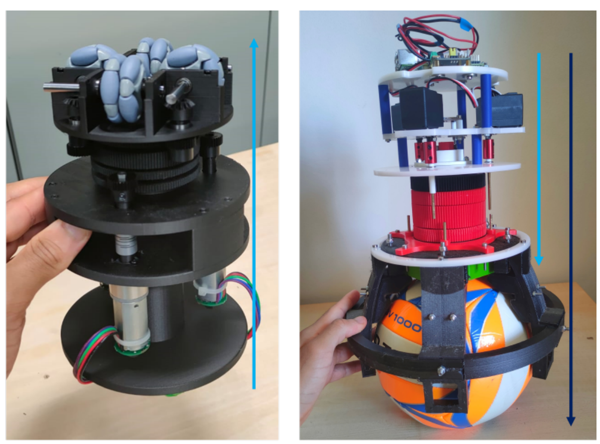
Both robots integrate the 3-channel transmission system (Fig. 7). The first prototype uses radial bearings, while the second incorporates the thrust-bearing configuration introduced earlier. The first prototype measures 18 cm in height, with a transmission size of 3×6 cm (height x diameter). The second prototype measures 20 cm from electronics to omni-wheels and nearly 40 cm including the ball, with a transmission size of 7×8 cm.

Several experiments were conducted to evaluate motion independence, with two representative tests presented here. As the prototypes are not equipped with sensors at this moment, performance was evaluated qualitatively through visual observation across multiple trajectories. Both tests were performed without the spherical ball stage, with the omni-wheels directly contacting the ground.

The first experiment aimed to observe drift under independent channel control. The robot was commanded to follow a square trajectory using a simple offline control strategy. In the absence of drift, the robot should return to its initial position after each square. Fig. 8 shows frame-by-frame tracking of an omni-wheel during this motion. A small drift of approximately 5 cm, representing 5% of the total distance traveled (≈ 1 m), was observed. This drift accumulates over successive squares and varies between trials. As no parasitic motions were observed on the other channels, repeated experiments indicate that the drift is mainly caused by omni-wheel rolling imperfections rather than channel interference. This first experiment also showed that translational motion can be achieved without unintended rotation.

The second experiment commanded pure rotational motion while maintaining zero linear velocity. Using the controller described in Section 4.2, the system successfully compensated for rotation-induced coupling, as confirmed by the observation of pure rotation without linear drift.

Both prototypes achieved independent control of linear and rotational velocities, demonstrating the mechanical robustness of the transmission. The main limitation of the current design is the strength of the gear teeth. While three-channel systems were successfully implemented using 3D printing, extending the design to additional channels would likely require precision-machined components to ensure adequate strength and alignment. Also, friction and wear were minimal in our small-scale prototypes, but they should be evaluated for higher loads or continuous operation. These experiments, demonstrating the transmission's motion independence, are also illustrated in the demonstration video referenced in Section 1.



a) 1st prototype, upside down (omits the ball)

b) 2nd prototype (with the ball)

Fig. 7: 3D printed omnidirectional robot's prototypes using our 3-Channels coaxial transmission design.

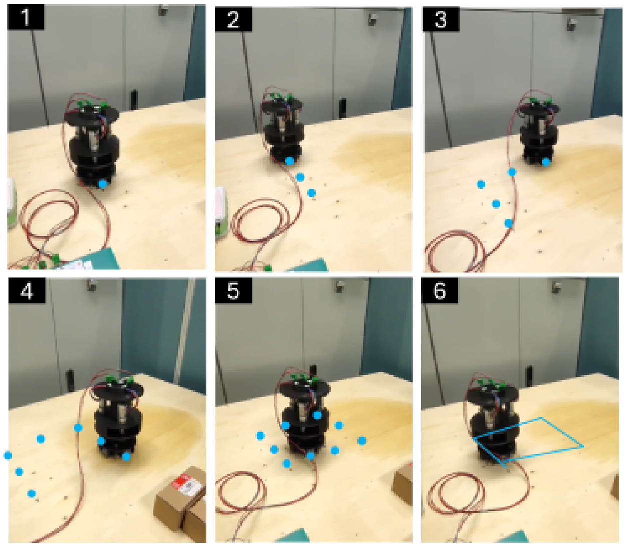


Fig. 8: Frame-by-Frame tracking of an omni-wheel position during square trajectory (First Prototype).

6 Conclusions

This paper presented a coaxial multi-channel rotary transmission system capable of transmitting multiple independent continuous rotary motions along a shared axis. Using a concentric architecture, the proposed design provides a compact and scalable solution for applications requiring several independent degrees of freedom while preserving symmetry and motion independence. Although the experimental validation focused on a three-channel configuration, the architecture can be extended to additional channels depending on structural constraints such as diameter and strength. To demonstrate its practical feasibility, the transmission was integrated into two omnidirectional ball robot prototypes. Experimental results confirmed mechanically decoupled operation without inter-channel interference, validating the effectiveness of the proposed approach. Future work will investigate further miniaturization and explore applications in other robotic and mechatronic platforms.

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