COSMOS: Design of a Differential Holonomic Robotic Drive System

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***Abstract*—In mobile robotics, the most common methods of movement are tank and mecanum drive systems. Tank drives allow for powerful forward and backward motion with high force efficiency, while mecanum drives enable smooth holonomic (omnidirectional) motion but lack strong pushing power. At COMET VEXU, we are proud to present COSMOS, a novel differential holonomic drivetrain that combines the strength and efficiency of a tank drive with the versatility of holonomic movement. The goal of this research is to design and structurally analyze a drivetrain system that optimizes motor power usage through efficient wheel arrangements while maintaining high maneuverability and control. By merging the best aspects of both drive systems, this project aims to enhance overall robot performance and demonstrate a new approach to mobile robot locomotion.**

***Index Terms*—Robotics, Mobile Robots, Robot Locomotion, Holonomic Drive, Differential Swerve**

I. INTRODUCTION

Mobile robotics relies on efficient drivetrain systems for locomotion across various environments. The two most prevalent configurations are Tank Drive (Fig. 2a) and Mecanum Drive (Fig. 2b). Tank Drive provides strong linear motion and excellent pushing power, making it ideal for high-torque applications. However, its inability to move laterally limits overall maneuverability [2].

Mecanum Drive enables full holonomic motion, allowing movement in any direction without reorientation. While this improves mobility, it sacrifices pushing power and power efficiency, making it less effective in strength-demanding scenarios [3].

These trade-offs necessitate a drive system combining Mecanum's mobility with Tank Drive's efficiency. This paper introduces COSMOS, a differential holonomic drivetrain addressing these requirements through innovative mechanical design and control systems.

II. RELATED WORK

There are many different approaches to designing holonomic drive systems, which are generally divided into two main categories: *coaxial* and *differential*. Common off-the-shelf implementations of holonomic systems typically use the coaxial configuration, where each motor independently controls a single axis of motion. In contrast, differential designs use paired motors that work simultaneously to generate combined motion along multiple axes.

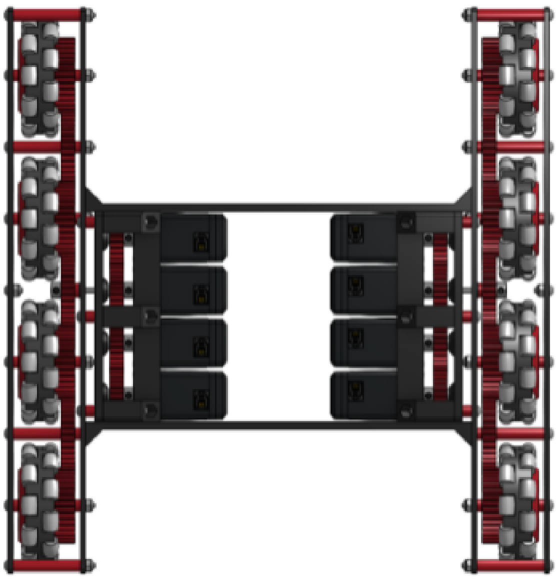
Fig. 1: Complete drivetrain assembly of COSMOS

TABLE I: Comparison of Drive System Characteristics

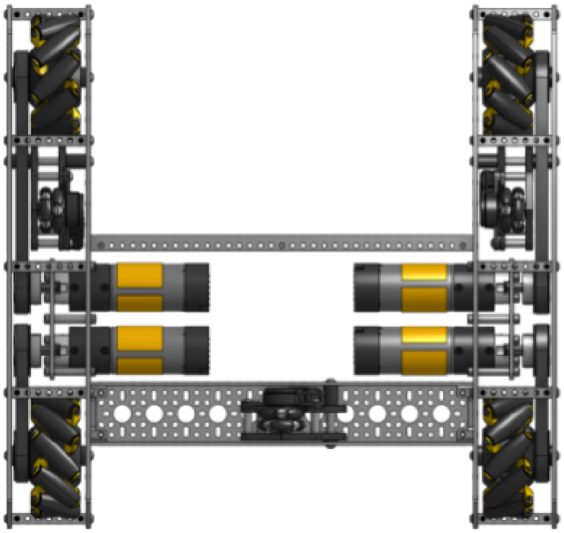
Feature	Tank Drive	Mecanum Drive	COSMOS
Mobility	Non-holonomic	Holonomic	Holonomic
Pushing Power	High	Low	High
Efficiency	High	Low	High
Mechanical Complexity	Low	Medium	High
Control Complexity	Low	Medium	High
Lateral Movement	No	Yes	Yes

Coaxial swerve mechanisms are highly effective and have seen successful application in a variety of robotics platforms, including NASA's Modular Robotic Vehicle (MRV). These systems offer excellent maneuverability and mechanical simplicity, although they can be limited by the complexity of integrating multiple drive axes and managing power distribution between them.

Differential holonomic systems, on the other hand, typically involve the use of bevel gears with top and bottom gears mechanically layered and connected through a central shaft. This configuration allows for complex, efficient motion control using fewer motors than coaxial systems. However, differential mechanisms present significant challenges in terms of high



(a) Tank Drive System



(b) Mecanum Drive System

Fig. 2: Conventional drive system configurations, Tank Drive and Mecanum Drive which are commonly used in mobile robots across the world

Fig. 3: This is an example of a Coaxial Based Drive system developed by MK4i Coaxial Swerve Module by Swerve Drive Specialties

Fig. 4: Example of a common method of a developing a Bevel Gear differential

manufacturing cost, limited availability of off-the-shelf components, and assembly difficulties.

Our proposed COSMOS design seeks to address these issues by offering a more accessible, cost-effective, and modular approach to differential holonomic drive construction.

III. DESIGN OF THE DRIVE SYSTEM

The COSMOS drivetrain employs a differential swerve system powered by VEX V5 motors, optimized for mobility and torque output within the V5 motor platform's constraints. Unlike traditional Mecanum or X-drive systems relying on perpendicular force vectors (often causing energy loss through force cancellation), the differential swerve approach separates motor outputs into rotational and translational components [1].

Each wheel module (Fig. 5) comprises a differential pod powered by two V5 Smart Motors. These motors collaborate through a compact gear assembly enabling simultaneous wheel rotation and module steering. This configuration ensures all motors remain actively engaged, significantly improving energy efficiency compared to traditional swerve or mecanum drives.

The drivetrain assembly (Fig. 1) features four differential

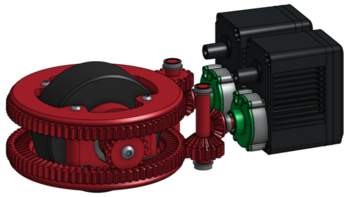


Fig. 5: Differential pod design of COSMOS, where we use a bevel gear design to use the torque of both motors for better force efficiency

pods mounted at each corner of a low-profile chassis. This layout minimizes the center of gravity while maintaining accessibility for maintenance and wiring. Symmetrical pod positioning balances torque distribution and reduces frame stress.

The VEX V5 system's precision control capabilities—particularly integrated motor encoders and smart ports—enable fine-tuned state estimation and closed-loop control, supporting stability and adaptability across various driving conditions.

IV. Programming and Control

The control system implements vector-based motion control with PID feedback loops for precise omnidirectional movement. Each swerve module is managed through real-time calculated translational and rotational inputs.

A. Vector Decomposition

Motion commands are decomposed into translational ($\vec{V_t}$) and rotational ($\vec{V_r}$) components. These vectors sum to produce target vectors ($\vec{V_{target}}$) for each differential pod:

$$\vec{V_{target}} = \vec{V_t} + \vec{V_r} \tag{1}$$

This decomposition enables smooth module coordination, ensuring consistent motion regardless of direction or rotation.

Pod rotation is limited to $\leq 90^\circ$ to minimize response time by always taking the shortest path to target orientation. After computing final target angle (θ_{target}) and velocity (v_{target}), differential kinematics translate these parameters into specific motor outputs.

B. PID Control

A PID controller continuously compares current pod angle ($\theta_{current}$) to the target angle:

$$e(t) = \theta_{target} - \theta_{current}(t) \tag{2}$$

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \tag{3}$$

where $u(t)$ is the control output, and K_p, K_i, K_d are proportional, integral, and derivative gains, respectively.

V5 Smart Motor encoders provide closed-loop feedback, significantly improving steering and translation accuracy.

C. Swerve Kinematics

Swerve kinematics map desired robot movement to individual wheel speeds and steering angles [4], [5]. Each pod's motion is defined as a function of the robot's desired velocity ($\vec{V_{robot}}$) and angular rotation (ω).

Each wheel's velocity vector is determined based on the robot's center of rotation and the wheel's relative position:

$$\vec{V_w} = \vec{V_{robot}} + \omega \times \vec{r_w} \tag{4}$$

where $\vec{r_w}$ is the position vector from the robot's center to the wheel.

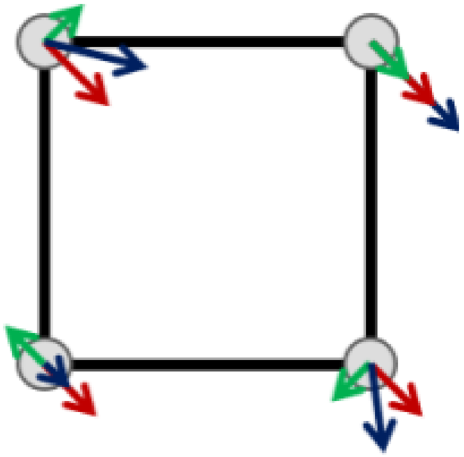


Fig. 6: Swerve kinematics diagram, each arrow translates to a different corresponding vector for each translation

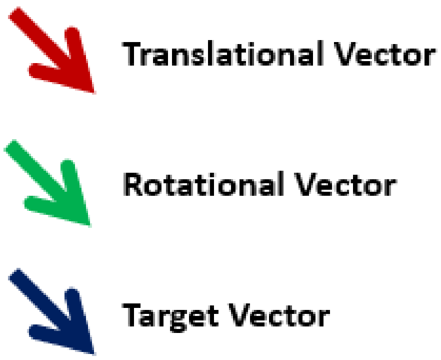


Fig. 7: Vector arrow correlation for the figure above and each color correlating to a different kind of goal

The combination of differential kinematics and closed-loop control maintains smooth, precise motion during complex maneuvers. The VEX V5 Brain's real-time processing enables high-frequency control signal updates, ensuring stability during rapid directional changes.

V. Testing and Observations

Finite element analysis (FEA) and physical single-pod testing evaluated the differential swerve pod's mechanical integrity and performance, confirming the design supports expected loading conditions while maintaining stability and motion precision.

A. Stress Analysis

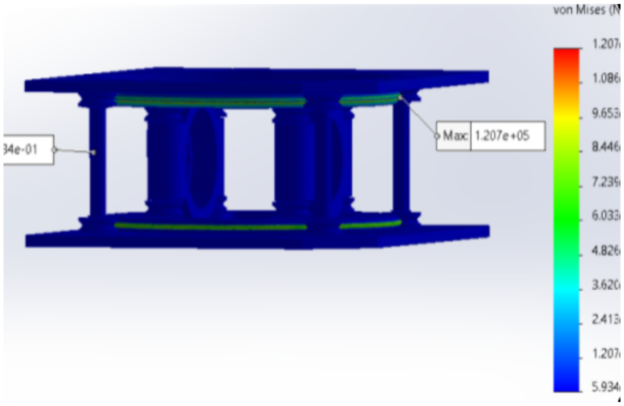
Two simulations analyzed force and torque conditions on the swerve pod.

First Test (Force):

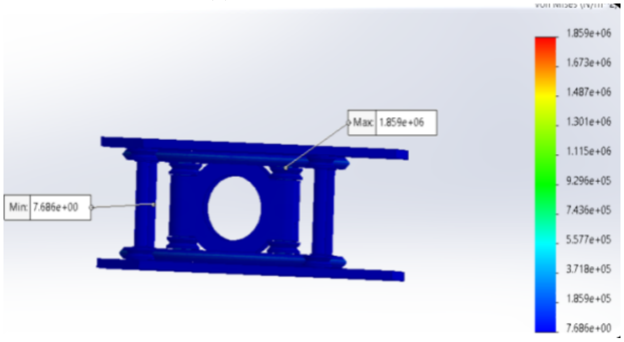
- Each pod supports 22.2 N (approximately ¼ of total robot weight)
- Maximum von Mises stress: 1.859 MPa (well below ABS-PC tensile strength of 40 MPa)
- Highest stress occurred around spacers due to reduced cross-sectional area

Second Test (Torque):

- Applied torque: 0.43 N·m
- Maximum von Mises stress: 120.7 kPa (safely under material limit)
- Stress concentration near cover plate center due to sharp corners
- Minor frictional effects observed between top plate and bearings



(a) Stress test - Force



(b) Stress test - Torque

Fig. 8: Finite element analysis results of the swerve modules with ABS in SolidWorks of different kind of stresses that are applied

B. Single Pod Testing

A single differential pod was assembled and tested independently to validate the control system before full-scale integration.

Testing demonstrated:

- Smooth bidirectional rotation and precise vector alignment
- Differential motion mapping correctly translates vector targets to motor outputs
- Motor feedback loops respond accurately to angle corrections (3-5° error)
- Pod alignment time averaged under 0.4 seconds for 90° turns

Initial PID gain imbalances caused minor oscillations, minimized through tuning proportional and derivative terms.

Fig. 9: Single pod movement test, where we input random positions and velocities and see how the swerve pod performs

These findings validated the drivetrain's control logic and physical reliability, supporting scalability to a full four-pod configuration for complete holonomic mobility.

VI. FUTURE PLANS

The differential holonomic drive enables several real-world applications beyond competition use:

A. Automotive Applications

Future iterations could adapt the drivetrain for automotive systems, enabling easier parking and tighter maneuvering without sacrificing torque and stability. This could simplify parallel parking, improve mobility in tight spaces, and support autonomous vehicle development.

B. Space Exploration

The drivetrain's efficiency and adaptability make it ideal for planetary rovers traversing rough, unpredictable terrain. Maintaining torque while offering full directional control could improve navigation on rocky, uneven surfaces with enhanced stability and energy efficiency—critical for power-constrained missions.

C. Industrial Use

In warehouse and industrial environments, differential holonomic drive systems could enhance payload capacity and maneuverability. Robots could navigate crowded spaces efficiently while providing necessary pushing power for material transport.

These directions aim to evolve the drivetrain from a competition concept into a real-world solution improving mobility across robotics, automotive design, and space exploration.

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