Design of a 4-Wheel Steering and Driving Robotic Platform

Kshitij M Bhat
Supervisors: Dr. Devendra Deshmukh,
Dr. Thiago E. Alves de Oliveira [1]

Department of Mechanical Engineering
Indian Institute of Technology Indore

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[1]Department of Computer Science, Lakehead University

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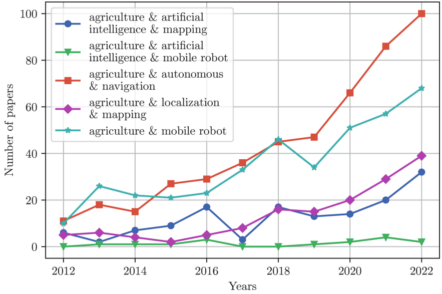
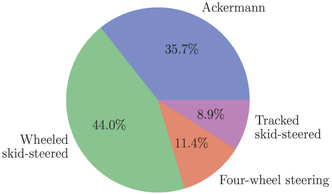
Definition of the problem

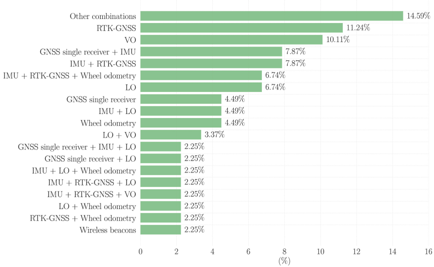
As the global population continues to grow, there is a growing demand for increased agricultural production while simultaneously prioritizing environmental preservation. Modern agriculture faces the challenge of optimizing crop yield while minimizing resource utilization and environmental impact. To address this challenge, the development of innovative agricultural tools and the utilization of robotic devices, particularly autonomous robots are imperative. However, existing solutions involve inefficient steering systems, such as skid-steer, which lower the accuracy of wheel-odometry, crucial for autonomous navigation algorithms. Four-wheel Steering and Driving (4WSD) robot configuration presents a promising solution for this problem. Although commercial 4WSD robots exist, they are expensive, not customizable for different crops and have proprietary hardware and software.

Robotics in Agriculture



Number of papers over the year of publication [Tiozzo Fasiolo et al., 2023]





Localization approaches

Literature Review

Steering Modes

Ackermann

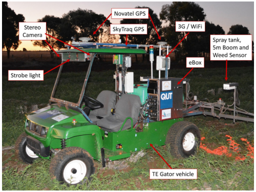
- Widely used
- Only two wheels steer
- No slippage
- Accurate wheel odometry

Skid-Steer

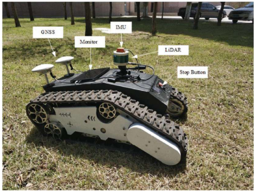
- Zero-radius turn
- Mechanical simplicity
- Slippage
- Inaccurate wheel odometry

4-WSD

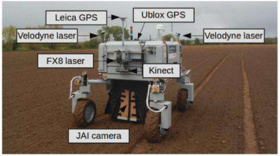
- Zero-radius turn
- Highly maneuverable
- No slippage
- Accurate wheel odometry



[Ball et al., 2016]



[Gao et al., 2021]



[Biber et al.,]

Literature Review

[Bak and Jakobsen, 2004]

BOSCH Bonirob, [Biber et al.,]

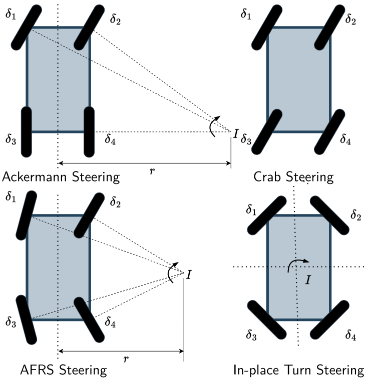
[Cariou et al., 2009]

[Saga Robotics Thorvald]

Novelty

The robot is designed based on the following novel features:

- Holonomic Design with 8DOF - Enables independent movement of steering and driving modules
- Modular Design - The robot is composed of 4 modules, where a Steering and a Driving unit forms a module
- Reconfigurable Design - The length and width of the robot can be changed based on the crop spacing



Steering Modes of the 4WSD Robot

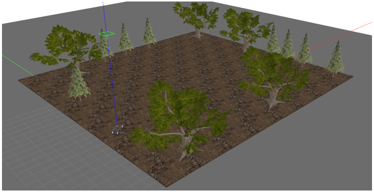
Methodology and work plan

Expertimental Model

1. CAD Design
2. 3D Printing
3. Assembly & Design Iteration
4. Electronics & PCB Design
5. Software for low-level control (`ros_control`)
6. PID Tuning

Simulation

1. Robot Model in Gazebo Simulation
2. Creation of agricultural terrain-like environment for testing
3. Sensor simulation & integration
4. Localization Algorithms (Extended Kalman Filter)



Gazebo environment

Modelling

$$\mathbf{q} = [x, y, z]^T \quad \boldsymbol{\omega} = [\omega_1, \omega_2, \omega_3, \omega_4]^T \quad \mathbf{F}_x \text{ - longitudinal force}$$

$\boldsymbol{\lambda}$ - longitudinal slip ratios $\boldsymbol{\alpha}$ - side-slip angles, $\boldsymbol{\tau}$ - torque $\mathbf{F}_y$ - lateral force

Kinematic Model

$$\mathbf{v} = [v_x, v_y, \dot{\psi}]^T$$

$$\mathbf{T}_{wx} = \begin{bmatrix} \cos\delta_1 & \sin\delta_1 & \frac{t}{2}\cos\delta_1 + \frac{L}{2}\sin\delta_1 \\ \cos\delta_2 & \sin\delta_2 & \frac{t}{2}\cos\delta_2 - \frac{L}{2}\sin\delta_2 \\ \cos\delta_3 & \sin\delta_3 & \frac{t}{2}\cos\delta_3 - \frac{L}{2}\sin\delta_3 \\ \cos\delta_4 & \sin\delta_4 & \frac{t}{2}\cos\delta_4 + \frac{L}{2}\sin\delta_4 \end{bmatrix}$$

$$\mathbf{T}_{wy} = \begin{bmatrix} -\sin\delta_1 & \cos\delta_1 & \frac{L}{2}\cos\delta_1 + \frac{t}{2}\sin\delta_1 \\ -\sin\delta_2 & \cos\delta_2 & \frac{L}{2}\cos\delta_2 + \frac{t}{2}\sin\delta_2 \\ -\sin\delta_3 & \cos\delta_3 & -\frac{L}{2}\cos\delta_3 - \frac{t}{2}\sin\delta_3 \\ -\sin\delta_4 & \cos\delta_4 & \frac{L}{2}\cos\delta_4 - \frac{t}{2}\sin\delta_4 \end{bmatrix}$$

Solve:

$$\mathbf{v}_{wx} = \mathbf{T}_{wx}\mathbf{v} = r_w\boldsymbol{\omega}$$
$$\mathbf{v}_{wy} = \mathbf{T}_{wy}\mathbf{v} = \mathbf{0}$$

Dynamic Model

$$\mathbf{M} = \begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & I_{zz} \end{bmatrix}, \quad \mathbf{C}(\mathbf{v}) = \begin{bmatrix} 0 & m\dot{\psi} & 0 \\ m\dot{\psi} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix},$$

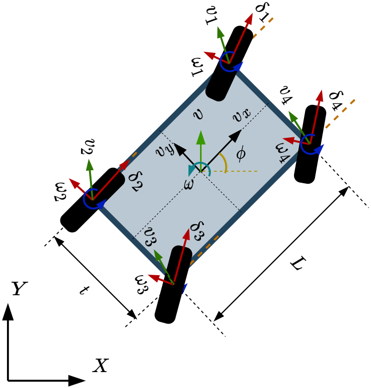
Solve:

$$\mathbf{M}\dot{\mathbf{v}} + \mathbf{C}(\mathbf{v})\mathbf{v} + \mathbf{g}(\mathbf{q}) = \mathbf{T}_{wx}^T\mathbf{F}_x + \mathbf{T}_{wx}^T\mathbf{F}_y$$

- Tire-Ground interaction model

$$\mathbf{F}_x(\boldsymbol{\lambda}) = \frac{mg}{4}\mu_x(\boldsymbol{\lambda}), \ \mathbf{F}_y(\boldsymbol{\alpha}) = \frac{mg}{4}\mu_y(\boldsymbol{\alpha})$$

Experimental Modelling



Top view of the 4-WSD robot

Odometry

$$\delta_f = \tan^{-1}\left(\frac{2\tan\delta_1\tan\delta_4}{\tan\delta_1+\tan\delta_4}\right) \quad \delta_r = \tan^{-1}\left(\frac{2\tan\delta_2\tan\delta_3}{\tan\delta_2+\tan\delta_3}\right)$$

$$a_f = \frac{\cos\delta_f(\tan\delta_f - \tan\delta_r)}{L} \quad a_r = \frac{\cos\delta_r(\tan\delta_f - \tan\delta_r)}{L}$$

$$v_f = r_w\sqrt{\frac{v_1^2+v_4^2}{2+(ta_f)^2/2}} \quad v_r = r_w\sqrt{\frac{v_2^2+v_3^2}{2+(ta_r)^2/2}}$$

$$v_x = \frac{v_f\cos\delta_f + v_r\cos\delta_r}{2} \quad v_y = \frac{v_f\sin\delta_f + v_r\sin\delta_r}{2}$$

$$v = \sqrt{v_x^2+v_y^2}$$

$$\omega = \frac{v_f a_f + v_r a_r}{2} \Rightarrow \phi = \sum \omega\Delta t$$

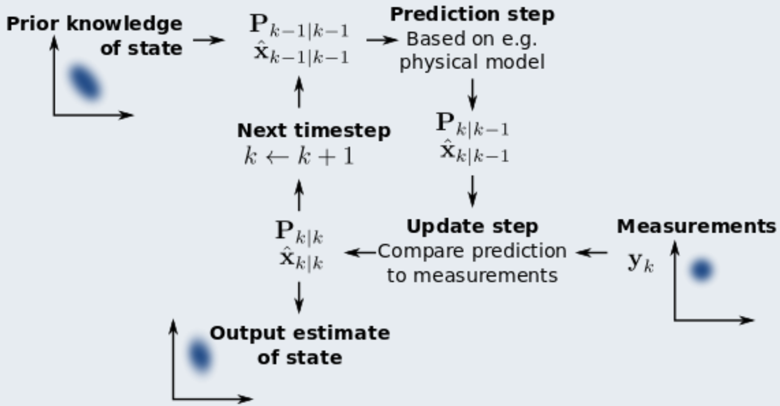
$$x = \sum(v_x\cos\phi - v_y\sin\phi)\Delta t$$

$$y = \sum(v_x\sin\phi + v_y\cos\phi)\Delta t$$

Localization

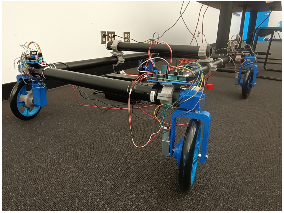
Determining where a robot is located with respect to its environment.

Extended Kalman Filter

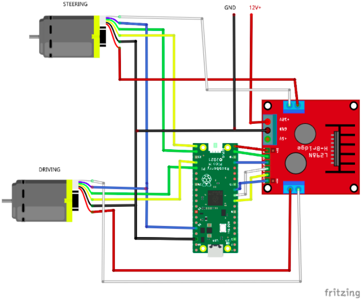


Design

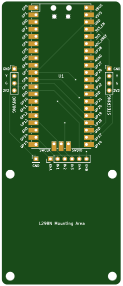
CAD Model



Prototype

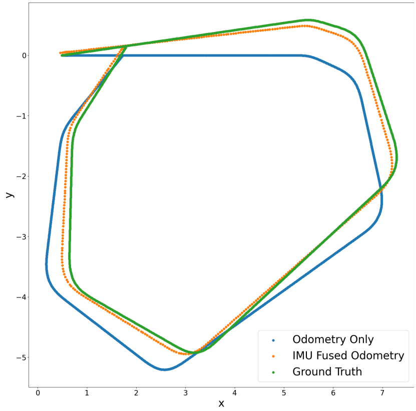


Wiring Diagram

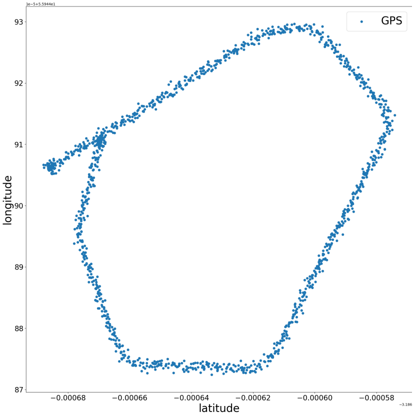


PCB Design

Results

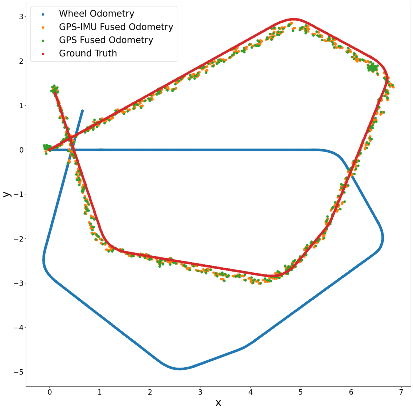


EKF IMU-Odometry Fusion

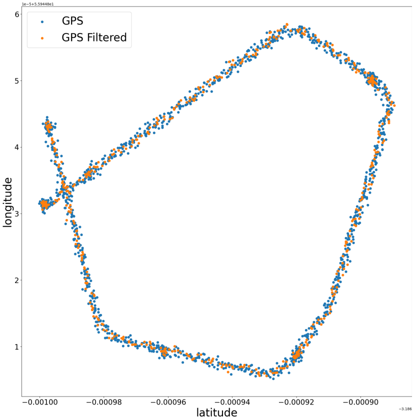


GPS data for the same run

Results

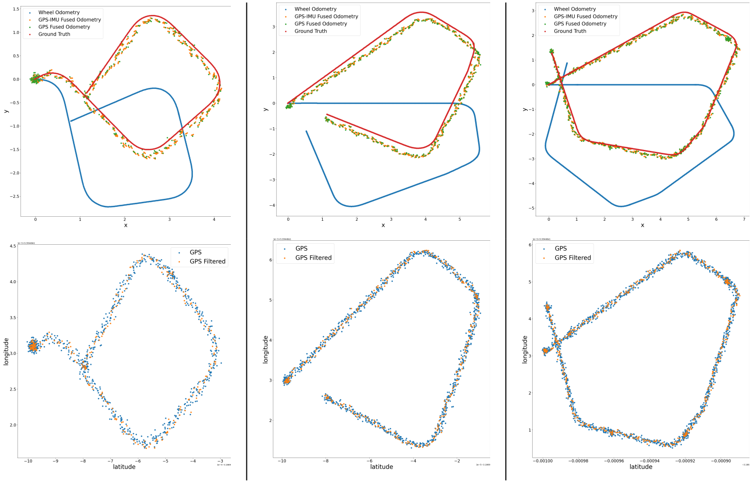


Comparison of Localization Estimates



Filtered GPS data

Results



EKF Localization results with GPS

Conclusion

The project demonstrates the following:

- Advantages of using a 4WSD robot for agricultural purposes such as crop analysis and weed detection.
- Design of a 4WSD agricultural robot involving a modular and reconfigurable design with easy assembly
- Low cost and mostly-3D-printed design coupled with commercial off-the shelf electronics makes the robot easy to manufacture
- Open-Source software based on the ROS and `ros_control` frameworks make the software highly accessible
- Kinematic and Dynamic modelling of a 4WSD robot configuration and suited navigation algorithms for autonomous capability

Recognition

Won the **first prize** with a prize money of Rs. 15,000 in the Idea Presentation competition themed: *"Innovations Towards Rural Development"* organized by Centre for Rural Development and Technology (CRDT), IIT Indore.

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