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Independent Offset Wheel Steering: An Improved Approach to Wheeled Mobile Robot Locomotion

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***Abstract*— In this paper, a new wheel configuration for mobile robot locomotion called IWOS (Independent Wheel Offset Steering) is presented. This approach offers quasi-omnidirectionality, collision detection and mitigation, expressive navigation capabilities with a simple mechanical design. First, an overall study of popular wheel designs and configurations is provided and then a detailed explanation of IWOS as well as it's distinct advantages are given. A proof of concept is shown using the physics simulation (GazeboSim) simulating various scenarios.**

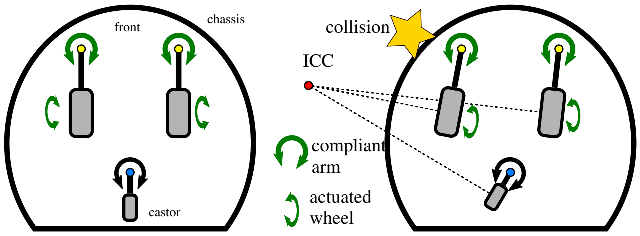

Fig. 1: IWOS with actuated/complient joints in green. A collision will be mitigated and the arms will be steered away from the contact point.

I. INTRODUCTION

During moving in a crowd or between people, collisions are inevitable. Currently, this problem is bypassed in mobile robotics by maintaining a sufficient safety distance to people and objects. This results in a very limited work-space for mobile robots or too long waiting times. The solution is a drive concept that mitigates collisions and dissipates the crash energy. In addition, a vehicle that can be pushed away and can also push people would be desirable. Such a technology, which is called compliance, is already used for robot arms.

Legged locomotion could solve this problem but has many disadvantages such as the mechanical complexity, power and energy efficiency. Therefore, wheel-based designs are preferred as they offer stability, maneuverability and are mostly easy to control [4][9].

A new wheel configuration, Independent Offset Wheel Steering (IWOS) shown in Fig.1, will be presented in this paper. Different wheel designs are being utilized in the field of wheeled locomotion, namely the standard wheel, castor wheel, Swedish wheel and spherical wheel. Each of them come with their particular strengths and weaknesses [4][9]. IWOS consists of two actuated wheels each mounted on a steerable (compliance controlled) arm and a passive castor wheel to support the chassis. This new approach combines some of the advantages of the compliance configurations, allowing for better maneuverability, collision detection and mitigation, as well as better human-robot interaction [7].

In the section Related Work, commonly-used wheel types and wheel configurations will be illustrated in order to cultivate a better understanding of the advantages offered by IWOS. In the following section, the physical configuration, advantages and a some of the distinct use cases such as collision detection and mitigation, expressive navigation and adjustable ICC (Instantaneous Center of Curvature) will be presented. The penultimate section Simulation presents preliminary results with GazeboSim. Finally, the results are discussed in the conclusion section.

II. RELATED WORK

In this section, a brief overview of the most common wheel designs and wheel configurations in use will be presented, as well as the criteria used to evaluate the pros and cons of each. Detailed kinematic models are not included in this section, since there is a quantity of detailed literature on the subject, exceeding the scope of this paper.

A. Wheel Design

There are four major wheel classes shown in Fig. 2, each with specific advantages and disadvantages. Each wheel class has its own specific kinematics which effects the overall kinematics of robot motion to a great extent [4][9].

1) Standard Wheel: This wheel class, as the name suggests, is the most basic design with two degrees of freedom, the first being around the wheel axle and the second one being over the contact point with the ground. The center of rotation passes through this point. In order to move in a direction other than the one that the wheel is facing, the wheel must be steered along a vertical axis [3][4][9].

2) Castor Wheel: This design is an extension of the standard wheel. It still has two degrees of freedom, but the second one is the rotation around an offset steering joint. This offset between the ground contact point and the center of rotation leads to a force being applied to the robot chassis during a rotation [2][3][9]. IWOS exploits this effect to detect a collision [7].

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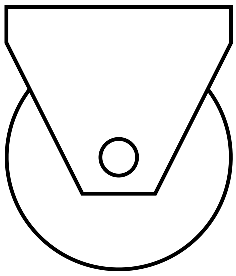
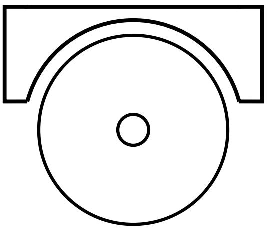


(a) Standard Wheel

(b) Castor Wheel[1]



(c) Spherical Wheel

(d) Swedish Wheel[2]

Fig. 2: Four most common wheel types

3) Swedish Wheel: In this wheel design, there are passive rollers along the wheel which help reduce friction in other movement directions.

There is an extra degree of freedom in comparison to the standard wheel: rotation around the rollers. The angle that the rollers are mounted dictates the direction with reduced movement resistance. For example, there is a 90-degree variant called Swedish 90, which allows for movement perpendicular to wheel orientation. The main advantage is the following: With only one actively-powered joint, moving in many different trajectories with little friction is possible [3][6][9].

4) Spherical Wheel: This design allows for true omni-directional movement. A spherical wheel can be powered to spin in any given direction. The main disadvantage lies in the difficulty of realization of this design [3][4][9].

A final consideration that must be taken into account is suspension. In order to maintain contact with the ground, proper suspension must be employed, especially when there are more than three wheels in a given configuration. The most primitive approach would be to use rubber tires around the wheels[9].

B. Evaluation Criteria for Wheel Configurations

Prior to discussing some of the common configurations used in the main types of wheels, a brief overview of evaluation criteria will be given. Those criteria are important in assessing the various pros and cons of any particular configuration.

1) Stability: The minimum number of wheels to achieve stability is just two. As long as the center of mass lies along the wheel axle, stability can be maintained. However, this configuration requires impractically large wheel diameters. In addition, motors with very high torque can lead to the robot making a third point of contact with the ground at initial start up.

The most common approach used to assure stability is to use three wheels. In this approach, the center of mass must remain inside the triangle formed by wheel's contact points. Although it is possible to further increase stability by using even more wheels, the resulting necessity for suspension diminishes the usability of such configurations [4][9].

2) Maneuverability: In mobile robotics, maneuverability is highly sought-after. The ideal scenario would be to achieve omni-directional movement, i.e. being able to move in any given direction, independently of where the robot is facing [2][3][4]. This can be obtained by Swedish or spherical wheels, however the mechanical complexity of realization is a deterrent.

Another approach to the achievement of omni-directional movement is to use four castor wheels with eight motors: four for spinning and four for steering. With this approach, even if the desired direction of motion is not ahead of the robot, castor wheels can be actively steered to reach the desired position. Furthermore, some robots can rotate on their own axes without changing their footprints. Although that would not be true omni-directional movement, it replicates the capability to some extent. This behavior can be achieved with a circular-shaped differential drive robot, which has its axis of rotation in the center[4][9].

Lastly, a car-like robot (Ackermann drive) has very poor maneuverability compared to the examples above. It has a turning radius larger than its footprint, and parking requires too many maneuvers[4][9].

3) Controllability: Usually, better maneuverability comes with worse controllability. This is due to more degrees of freedom offered by omni-directional designs. In order to achieve the desired motion, an increased amount of computation is required [8][9].

It should also be noted that the more maneuverability a design offers, the more difficult it is to maintain a robot's trajectory. For example, with an Ackermann drive, locking the front wheels is sufficient for travelling in a given direction, but with a differential drive, each wheel has to be kept at the same velocity with a precision which is not always easy to achieve[4][9].

All in all, there is no optimal wheel configuration that maximizes the advantages while minimizing the disadvantages. A configuration must be chosen based on its strengths for a given use case.

C. Common Wheel Configurations

In this section, a brief overview of frequently-employed wheel configurations will be given. Neither detailed kinematic models nor a great magnitude of small variations that

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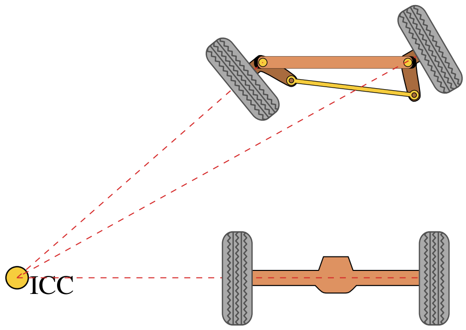

Fig. 3: Ackermann Drive [3]

utilize the general idea will not be covered, since it is beyond the scope of this paper.

1) Ackermann Drive: The Ackermann drive was developed in the mid-nineteenth century to achieve better maneuverability for coach-cars and is widely used in many commercial vehicles. The main idea behind the Ackermann drive was to provide steerable wheels with a correlated pivot, such that their axis intersect at a point with the rear wheel axis. This is achieved via an Ackermann linkage, which transfers the steering command to the wheels in such a way that they have different steering angles that satisfy the ICC without a slip in the wheels [1]. This relatively easy-to-understand concept is illustrated in Fig. 3.

This configuration is quite popular in hobby robotics, since it is relatively easy to use an RC car chassis. It offers poor maneuverability compared to an omni-drive but it is rather easy to control. This is a non-holonomic vehicle [3][4][9].

Fig. 4: Four Castor Wheels with eight motors - Nomad [4]

[3]User:Bromsklossderivative
work: Andy Dingley (talk) -Ackermann.svg, CC BY-SA 3.0,
https://commons.wikimedia.org/w/index.php?curid=11038290

2) Omni-Drive - Four Castor Wheels and Eight Motors: Omni-directionality can be achieved with four castor wheels that are actuated by four motors that control the individual spin of each wheel and four other motors that control the steering [5][9]. Nomad XR4000 shown in Fig. 4, which is no longer produced, employs this configuration. A similar configuration, independent four-wheel steering, is used in the robot Blue [10].

Fig. 5: Four Swedish Wheels - Uranus [5]

3) Omni-Drive - Four Swedish Wheels: This configuration has been employed in many research robots, e.g. on Carnegie Melon Uranus shown in Fig. 5. It provides for omni-directional movement, which allows movement in any given direction and can even rotate around its own axis at the same time. This can be achieved with different rotation directions and speeds on each wheel [9].

4) Skid-Steer Wheels: This configuration is usually employed in tanks and similar mobile robots that utilize threads instead of wheels. A very popular wheeled implementation is the "differential drive", which is very common in mobile robotics shown in Fig. 6. The underlying idea is to control the direction by employing different velocities in each wheel. There is no additional mechanism to control steering. The robot moves along a circle, dictated by wheel geometry and the velocity difference between wheels. Unlike any other drive configuration mentioned here, wheel slippage is unavoidable, making operating on certain ground types challenging. This is an non-holonomic vehicle [2][4][9].

D. Holonomic vs Non-Holonomic Constraints

The concept of holonomy has a very broad definition in mathematics. In mobile robotics, it specifically refers to kinematic constraints of the robot chassis.

[4]"Distributed temporal event mapping and fusion - Scientific Figure on ResearchGate. Available from: `https://www.researchgate.net/figure/The-Nomad-XR4000-mobile-robot_fig3_237445040`

[5]By Gwpcmu - Own work, CC BY 3.0,
https://commons.wikimedia.org/w/index.php?curid=11440618

[6]By NikNaks talk - gallery - wikipedia 11:44, 30 May 2010 (UTC) - DifferentailSteering.gif; original file: [1], CC BY-SA 3.0,
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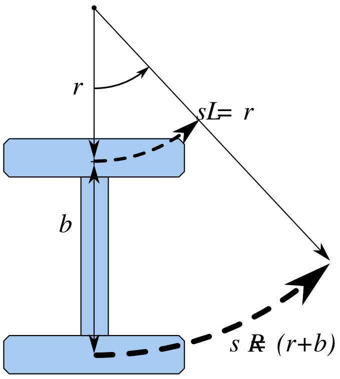


Fig. 6: Differential Drive [6]

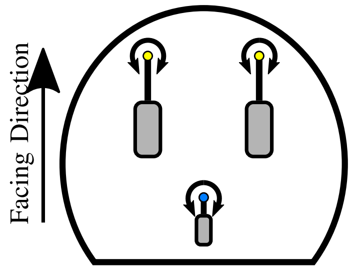


Fig. 7: Mechanical configuration

A holonomic robot has zero non-holonomic constraints whereas a non-holonomic robot has at least one non-holonomic constraint. Non-holonomic constraints are defined by a differential relationship of position variables and can not be integrated to acquire the position variable [9].

There is various literature on this topic that explains it in a detailed fashion for each application, but in a very broad sense it can explained in the following way: An omnidirectional drive is holonomic since it allows movement in any given direction. This can also be expressed as ”having number of degrees of freedom equal to the number of coordinates needed to specify the configuration of the system” [5]. On the other hand, an Ackermann drive or a skid/steer configuration is non-holonomic and can not move to every desired position directly [3][4].

III. INDEPENDENT OFFSET WHEEL STEERING

In this chapter, a new approach for wheeled mobile robot locomotion will be presented. First, the mechanical configuration will be illustrated. Following that, four uses cases that would maximize the advantages of this configuration will be given.

A. Mechanical Configuration

The fundamental mechanical configuration consists of two standard wheels attached at the end of two steerable arms parallel to the ground which connect to the robot chassis and a third passive castor wheel. There are four motors in total, two for each arm in which one motor is used for spinning the wheel and the other for steering the arm. The third wheel is not motorized and adjusts itself to the ICC (Fig. 7).

The arms have preferably the same length and the wheels, the same diameter. They are attached to the robot's chassis on the front (relative to the robot's default direction of movement) and the wheels are attached to the arms further back relative to the steerable arm contact point. Ideally, they should be placed symmetrically on the chassis.

The third wheel has a smaller wheel diameter compared to the wheels attached to the arms and is closer to ground. It is also located further back compared to the steerable arms.

The arms are steerable to a limited range, allowing for a steering angle of less than 180 degrees. The key point here is that the steering is done at an offset from the ground contact point, allowing the robot chassis to change its orientation independent of the actual driving direction.

The robot chassis has preferably a circular or semi-circular shape, which is to its advantage in collision mitigation.

B. Possible Use Cases

IWOS offers various possibilities that can be utilized in wheeled locomotion. In this section, four distinguishing use cases will be presented.

1) Collision Mitigation: In the event of a collision, the steerable arms experience a torque which changes their orientation in such a way that the robot chassis automatically turns away from the point of collision. This could be used in a non-motorized use case of steerable arms, for example, stabilized by springs (Figure 1).

In the case of proposed active steering, once a collision has been sensed, the steerable arms could be actively controlled to steer away from the point of collision.

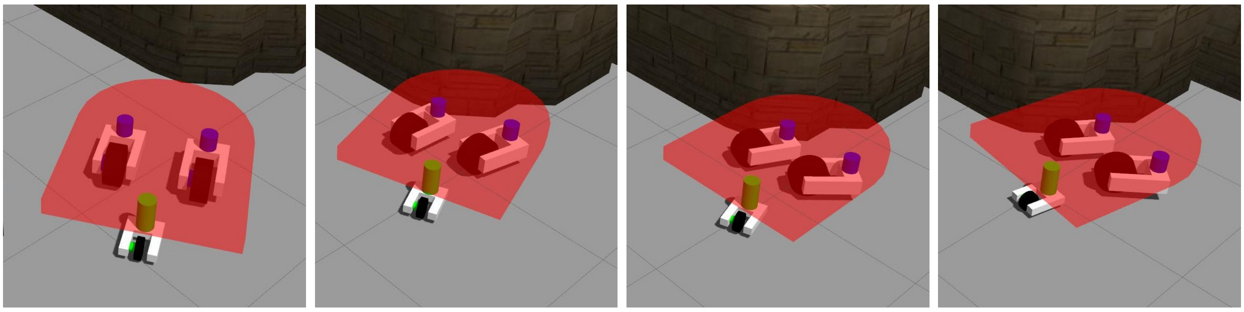
In both cases, a collision would be mitigated and any possible damage to the robot chassis or to the collision point would be considerably reduced.

If contact with the collision point is maintained, a sliding motion could be achieved rather than a head on crash with a small adjustment to the steerable arm's orientation. To further enhance this behavior, small wheels could be horizontally mounted to the front of the robot. Those small wheels would assist the robot greatly even in the case of a high friction environment.

2) Lateral Collision Detection: In the case of a lateral collision, the robot chassis would experience a force from the collision point. This force would be transferred to the steering arms, forcing them to change their orientation. With a simple pressure sensor or with proper torque control of the motors, the torque experienced could be processed to determine the direction of collision. This could be further used to mitigate damage resulting from a collision (not avoidance, since a collision would have already happened).

It is more suitable to have a circular or a semi-circular chassis in order to better transfer the collision force experienced as torque into the steerable arms.

3) Expressive Navigation: Signaling: Many mobile robots face the momentary direction in which they are driving rather



(a) The vehicle approaches an object with the steerable arms mounted on a spring.
(b) The vehicle is in contact with the wall and the collision has been mitigated.
(c) Due to the torque applied, the springs that hold the steering arms twist and steer the vehicle away from the object.
(d) The vehicle is steering away from the object. Because of the passive suspension, the vehicle will follow the wall.

Fig. 8: Collision mitigation and recovery. An IWOS vehicle is capable of mitigating the collision and leading the vehicle away from the contact point.

than their desired goal position. This causes problems, especially in environments with humans, since this movement is counter-intuitive and makes it harder for humans to predict robots' behavior.

Thanks to the fact that there is an offset between the wheel-ground contact point and robot-steerable arm connection, a mobile robot using IWOS possesses the capability of driving in a direction that differs from the direction it faces. The robot can rotate its front without changing its driving direction, allowing it to signal upcoming changes in movement. This feature can be especially useful in indicating evasion maneuvers in narrow environments shown in Fig. 9.

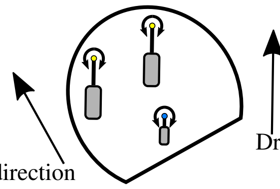
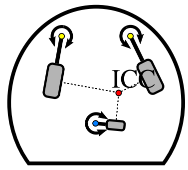


Fig. 9: The actual driving direction differs from the actual facing direction and can signal upcoming turn maneuvers to humans.

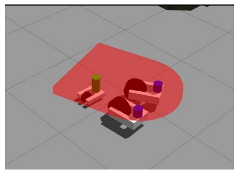
4) Adjustable ICC: Better Maneuverability and Collision Avoidance: Another advantage offered by IWOS is that of being able to adjust the ICC solely by steering the arms. Depending on the arm orientation, the ICC can be under the robot's footprint, which allows for rotation along a very small circle or even at its own axis. Another possibility is to have the ICC away from the robot, which allows for better maneuverability. The ability to place the ICC on different locations makes IWOS nearly omni-directional; only the maximum steering angle dictated by the arms hinders omni-directionality shown in Fig. 10.

C. Advantages

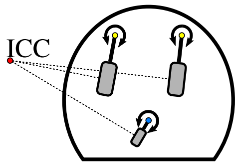
IWOS presents many advantages compared to its popular counterparts. In this section those advantages will be listed and briefly explained.



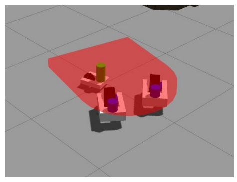
(a) ICC inside



(b) GazeboSim - ICC inside



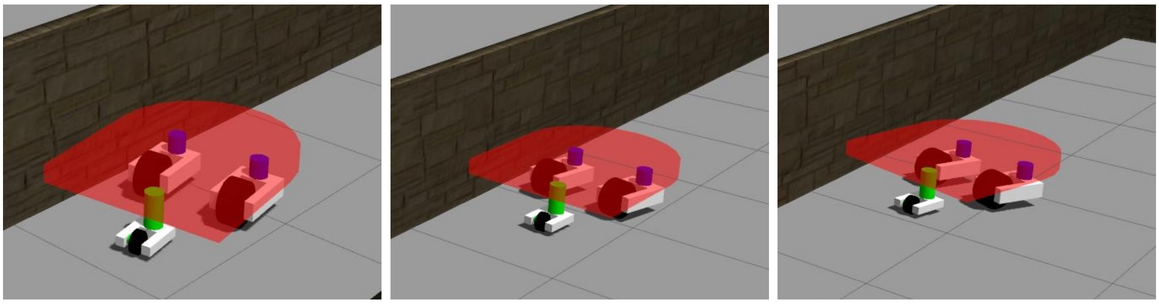
(c) ICC outside



(d) GazeboSim - ICC outside

Fig. 10: IWOS offers adjustable ICC only by steering the arms.

- High Maneuverability: IWOS has nearly omni-directional movement capability.
- High Controllability: Although high controllability doesn't usually come hand-in-hand with high maneuverability, with IWOS it is possible to control the robot with limited effort. It is even possible to run any pure differential drive navigation method by just locking the steerable arms.
- Better Collision Recovery: In the event of a collision, going backwards is not the only option that IWOS has. Being able to move in a less limited way provides better collision recovery. In addition, possible sliding capability further enhances this advantage.
- Relatively Simple Mechanical Design: Operating with standard wheels and a castor, IWOS has a simpler mechanical construction.
- Better Human Interaction: Thanks to its ability to indicate future movements, IWOS presents a more intuitive human-robot experience.



(a) The vehicle will press itself parallel against the wall. A vehicle with differential drive would become wedged.

(b) The vehicle has contact.

(c) The vehicle is able to leave the contact without scratching itself further.

Fig. 11: Sliding motion that allows the contact with the collision point to be broken in a way that is not possible with a differential drive.

IV. SIMULATION & PRELIMINARY RESULTS

A vehicle that employs IWOS has been simulated With ROS and GazeboSim to test its advantages. To minimize vehicle control, a spring with constant torque have been mounted on each steerable arm. Fig. 8 demonstrates how the vehicle behaves in an event of collision. The vehicle steering leads the vehicle away from the contact and thus minimizes the impact. An active control can slow down the vehicle or change the steering angle. If the contact with the object is exactly in the middle, the arms would not experience a torque and not rotate. In this case an active control with contact sensors would be necessary to turn the vehicle away from the collision point.

Fig. 11 shows a vehicle driving parallel to the wall. Such a maneuver is critical with a differential drive because it can become wedged together with the wall. If a vehicle with a differential drive finds itself in this situation, it can at best be released by a reverse movement. If this is not possible, the vehicle must rotate while in contact with the object which can lead to possible damage to the vehicle or to the object. On the other hand, a vehicle with IWOS can break contact with the collision point by steering the arms which causes a lateral movement of the chassis. This enables the vehicle to drive away safely form the object.

V. CONCLUSIONS

IWOS combines many advantages of commonly-used wheel configurations in a rather simple mechanical structure. A simulation done in Gazebo which includes a proper physics engine, demonstrates preliminary results and illustrates some of the possible use cases. This approach presents itself as a valid and easily-implementable wheel configuration with many extra applications that are begging to be explored.

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