A Modular Wheel System for Mobile Robot Applications

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Abstract

This paper introduces a modular all–in–one wheel system for combined steering / driving applied to service robots operating in indoor environments like homes, offices, or hospitals. The wheel system is based on standard tires, builds very compact, and provides a high pay load to dead load ratio. It is used as a building block to construct a wide variety of highly maneuverable mobile robots ranging from simple tricycles to fully holonomic locomotion platforms. Integration is simple, because each wheel system is equipped with the necessary control and communication infrastructure based on standard PC components.

1 Introduction

This paper proposes a universal and modular wheel system including all the necessary mechanics, power electronics, the control system, and a communication interface. It is designed for use in highly maneuverable mobile robots operating in indoor environments. An increased interest in manufacturing such robots exists. However, development still takes a lot of time, since it requires diverse know–how ranging from motor control to navigation.

Constructing a robot from pre–built universal modular components shortens the development period. For example, the proposed modular wheel system can be used to quickly build almost all types of mobile robot platforms. This includes simple tricycle kinematics with two fixed and driven wheels and one steering wheel, all-wheel steered omnidirectional robots, and even fully holonomic robots based on actively steered and driven offset wheels.

There are some more advantages of a modular wheel system: In case of a failure, the module is replaced and repaired off–line. This reduces down–times of the robotic system. In addition, all the components like motors, gears, power electronics, and control algorithm are tuned upon another, and hence achieve optimal combined performance. This is not necessarily the case when building robotic platforms from scratch.

Many wheel systems for high mobility robots have been proposed in the literature. Universal wheels, i.e., wheels with freely rotating rollers, like orthogonal wheels, Mecanum wheels [9] or double wheels [8] achieve holonomic motion. These wheels lead to vibrations and are not well suited for driving on rough surfaces or carpets. Although some modifications like placing a spherical wheel between the universal wheel and the ground have been proposed [1], practical usefulness remains limited. Hence, most robotic vehicles rely on standard tires, where car–like or wheelchair–like kinematics [11] are by far the most prevalent. However, in combination with a robotic arm, omnidirectional platforms are advantageous, which are generally equipped with all–wheel steering. Fully holonomic vehicles can also be achieved with standard tires, when the wheels are mounted with an offset and are actively steered and driven [6, 7].

In this paper, a wheel system for combined steering and driving based on standard tires is proposed. The first prototypes have been built in 1993 and have been extensively tested with the mobile manipulator ROMAN [2]. This included high–accuracy mobile manipulation and high–speed transportation in indoor environments. Several hundred kilometers on varying floor materials (tiles, carpet, concrete) have been covered with velocities of up to 1.5 m/sec. Based on these experiments, the wheel system has been successively refined over the years.

The resulting design is introduced in Section 2: Section 2.1 describes the basic mechanics. A more advanced wheel system, which can be used as a building block for a wide variety of highly maneuverable mobile robots is presented in Section 2.2. The corresponding control and communication infrastructure integrated into the wheel system is the topic of Section 2.3. Section 3 covers a low–cost prototype implementation based on commercially available mechanical

(Section 3.1) and electrical (Section 3.2) components. For communication purposes, the Universal Serial Bus (USB) is used as an alternative to the Controller Area Network (CAN) Bus. The advantages of the USB, especially its real–time communication capabilities, are discussed in detail in Section 3.3.

2 The Modular Wheel System

In the following, we propose a family of modular wheel systems for both steering and driving based on standard rims and tires. They have the advantage of being very compact while providing a high pay load to dead load ratio. The wheel position with respect to the steering axis is given by two offsets O_{lat}, O_{long} according to Figure 1.

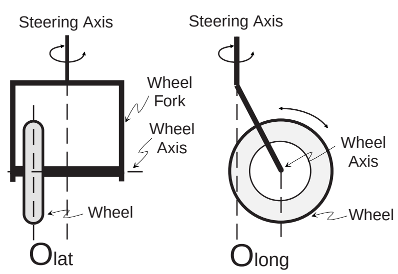

Figure 1: Definition of lateral offset O_{lat} and longitudinal offset O_{long}.

There are two major options for constructing combined steering/drive wheels: The first option is to fix the drive motor to the wheel. In this case, the steering motor not only reorients the wheel, but also the drive motor, which causes a higher moment of inertia. In addition, it is a problem to establish data and power connections to the drive motor. The second option is to keep both steering and drive motors fixed with respect to the robot chassis and transmit the drive power to the wheel via a gear mechanism. This results in a lower moment of inertia for the steering mechanism and hence, allows the use of less powerful and more compact steering motors. Furthermore, the wheel may turn without screwing up any cable connections.

The proposed wheel system constructed according to the second option is introduced in the next section.

2.1 The Basic Wheel System

The basic wheel system is depicted schematically in Figure 2. It comprises the following main components:

- hollow shaft motor and gear for steering
- motor and gear for driving
- vertical drive shaft
- miter gear
- wheel fork
- standard rim and tire

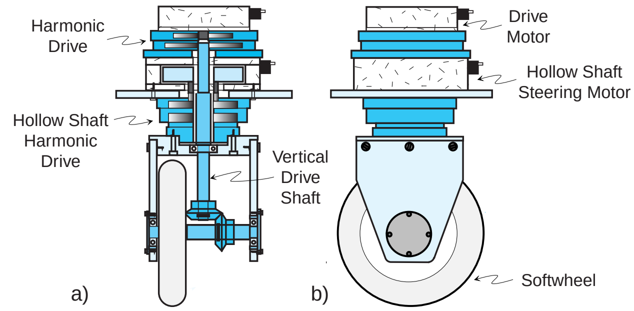

Figure 2: Schematical drawing of the basic wheel system for combined steering and driving a) front view (cross section) b) side view.

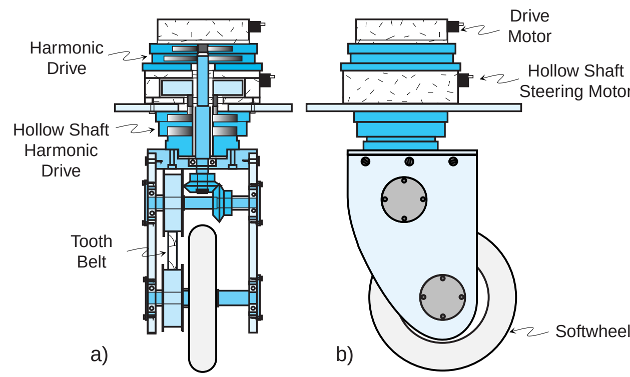

Figure 3: Schematical drawing of the advanced wheel system for combined steering and driving a) front view (cross section) b) side view.

Harmonic Drive reduction gears [3] are used for both steering and drive motors to transform motor speeds and torques to appropriate values. Being virtually backlash–free, these gears allow the use of low–resolution encoders mounted directly to the motors. The angular position of the gear output can thus be precisely determined with the encoder resolution times the gear ratio. In case of the steering motor, a harmonic drive gear with integrated bearings is employed, which further reduces the number of parts and simplifies manufacturing.

The drive motor torque is transmitted via the vertical drive shaft through the hollow shaft steering motor

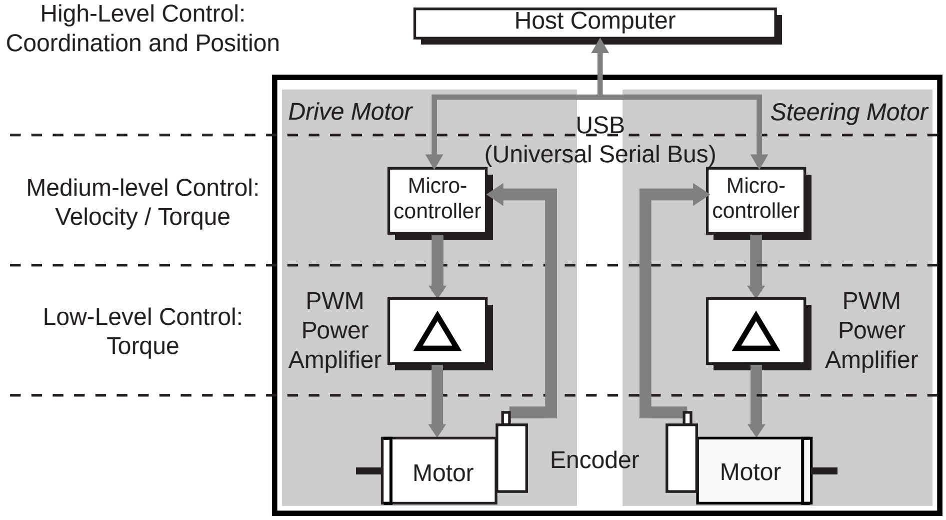

Figure 4: Hierarchical three–level control architecture.

and the hollow shaft harmonic drive gear. The miter gear then conveys the drive shaft torque to the wheel axis.

2.2 The Advanced Wheel System

The wheel system described so far just allows to choose the lateral wheel offset O_{lat} with $|O_{\text{lat}}| > O_{\text{lat}}^{\text{min}}$. When either $|O_{\text{lat}}| \leq O_{\text{lat}}^{\text{min}}$, for example $O_{\text{lat}} = 0$, or a longitudinal offset O_{long} is required, a small modification to the basic wheel system is in order, Figure 3. For that purpose, a tooth belt drive is added as a succeeding stage to the miter gear. Now, both the lateral offset O_{lat} and the longitudinal offset O_{long} can be chosen freely.

2.3 Control and Communication

Since the goal is to provide a modular wheel system, major parts of the control system not depending on the actual application are integrated into the module. For that purpose, every motor/amplifier is equipped with a microcontroller, which converts encoder signals to motor positions and generates appropriate motor commands. In addition, the microcontroller monitors the operation of motor and amplifier.

A hierarchical, three–level control architecture is employed, Figure 4. High–level control is performed by the host computer and consists of motion planning, wheel coordination, and position control. Medium–level control is done by the microcontrollers and covers motor speed or torque control. Low–level torque control is performed by an analog control loop. Medium–level and low–level control functionalities are fully integrated into the wheel system and are parametrized by the host computer.

3 A Prototype Implementation

In this section, a prototype implementation of the advanced wheel system described in Section 2.2 will be presented.

3.1 The Prototype Wheel Mechanics

As an example, a wheel system with zero lateral and longitudinal offset, i.e., $O_{\text{lat}} = 0$, $O_{\text{long}} = 0$ is considered, which is useful for building omnidirectional nonholonomic robots [2]. Since a low–cost solution based on commercially available components is preferred, some modifications are in order. For example, a hollow–shaft steering motor (Figure 2) with the appropriate power rating is difficult to obtain and rather expensive. Hence, it is replaced by a standard DC motor and a tooth belt drive. In contrast, the hollow shaft harmonic drive steering gear with integrated bearings is commercially available with gear reduction ratios of $50 : 1$, $100 : 1$, $120 : 1$, $160 : 1$. The required gear ratio is calculated as follows: In a typical service robot application, the steering wheel is reoriented with about 100 rpm. However, the maximum input speed of a harmonic drive is about 5000 rpm, the maximum speed of the considered motors is about

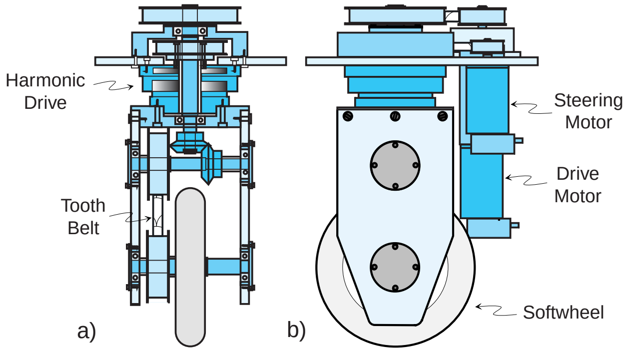

Figure 5: The wheel system based on commercially available components a) front view (cross section) b) side view.

7000 rpm. Hence, a tooth belt drive with a reduction ratio of 2.5 : 1 is added between the motor and a 50 : 1 harmonic drive. The required torque has been measured to be approximately 100 Nm with a rubber tire on concrete floor.

For a drive wheel diameter of 15 cm and a desired robot velocity of 1.5 m/sec, the wheel revolutes with about 150 rpm. For a motor with a maximum speed of about 7000 rpm, a gear reduction ratio of 30:1 would be required. However, harmonic drive gears with a gear ratio less than 50 : 1 are not yet available [4]. A combination of a planetary–type reduction gear and a tooth belt drive is thus used.

The prototype wheel system including these modifications is depicted in Figure 5. The motors are mounted overhead to reduce the overall height, and hence to lower the center of gravity. Two identical motors are used to reduce the total number of parts. These high efficiency MAXON motors [5] are very compact and possess the following characteristics:

length / diameter	70 mm / 40 mm
nominal voltage	48 V
idling speed	7160 rpm
permanent torque	0.232 Nm
maximum torque	2.64 Nm
maximum output power	487 W

Appropriate tires are critical for successful operation of service robots. Hard rubber tires, for example, are not suitable, because they lead to unacceptable platform vibrations when moving on rough surfaces. On the other hand, pneumatic tires are appropriate, because platform vibrations are reduced and unevenness of the ground is averaged out. However, pneumatic tires need a lot of maintenance. In addition, they deform permanently during long–time parking. Hence, a special type of foam–filled tires [10] is used, which are maintenance–free and do not suffer from permanent deformations. A tire diameter of 15 cm has been found to be a good compromise for most indoor applications.

3.2 Microcontroller–based Motor Control

A 48 Volt lead–acid battery is used as the main power source for the two motors. Each motor is driven by a pulse width modulated (PWM) power amplifier, which in contrast to linear amplifiers has a very low power dissipation. The PWM amplifiers are equipped with an integrated current control loop.

For velocity control and for PWM–signal generation, the widely used microcontroller SIEMENS 80C515 [12] is employed for each motor. The internal counters of the microcontroller are used to decode the motor direction impulses from the motor encoders. The program memory is divided into a random access (RAM) and a read only memory (ROM) area. The ROM contains basic I/O routines, control algorithms, and the watchdog–timer. The RAM holds parameters of the control–algorithm, which can be changed on the fly, cf. Section 2.3.

3.3 Host Communication via Universal Serial Bus (USB)

For closing the high–level control loop, a universal interface for communication with the host computer is required. The interface should be available for all major operating systems and computer architectures.

The Universal Serial Bus (USB) fits these requirements: It is the new peripheral bus standard for the widely used IBM–compatible personal computers and has been standardized by a number of companies including Compaq, Intel, Microsoft, and NEC [13]. In the mean time, a huge number of peripheral components like keyboards, scanners, and digital cameras [14] are available. Manufacturers of computer architectures which differ from the IBM-PC, plan to add USB support as well. At the moment, USB is available for the operating systems DOS, Windows 9x [15], Linux [16], FreeBSD [17] and NetBSD [18].

USB is a serial bus, which is especially important for modular devices, because the number of connections is reduced without sacrificing the data rate. The bus provides transmission rates of 1.5 Mbits/sec (low speed devices) and 12 Mbits/sec (high speed devices) with integrated cyclic redundancy check (CRC) error detection.

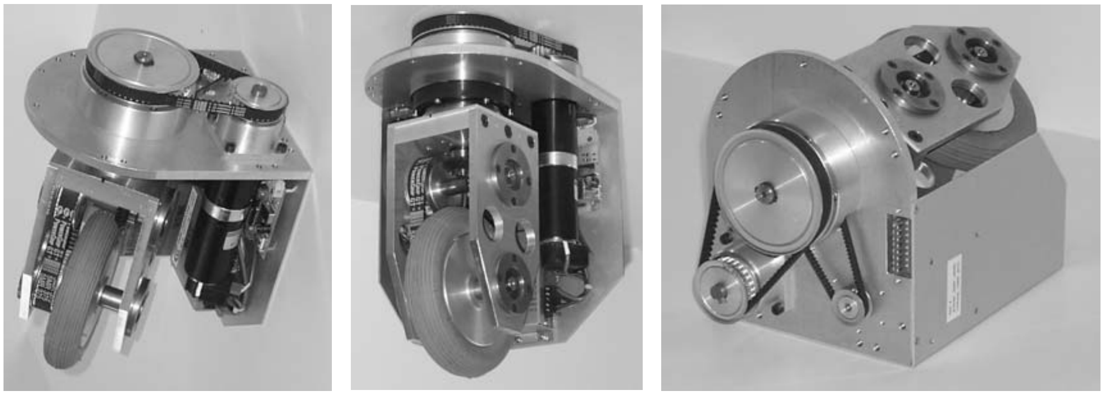

Figure 6: Different views of the prototype wheel system.

The USB is based on a client–server–architecture and a master–slave–protocol. It uses a tree topology with a maximum of 127 peripheral devices and 16 transfer channels per device. Hot attachment and removal of devices is supported, i.e., peripheral devices can be added or removed during operation.

In addition to data transfer, the USB also provides power supply for peripheral devices. Three device types are supported: low power bus–powered, high power bus-powered and self-powered devices. Bus–powered devices can draw up to 500 mA @ 5 V (high power) or 100 mA @ 5 V (low power) from the bus. The bus uses a shielded four–wire connection comprising a twisted pair data connection and two power leads. In our case, the microcontrollers are operating as low power bus–powered devices. As a result, the wheel system is connected to the outside world via two connectors: A two–wire 48 V power line and a four–wire USB connector.

Several characteristics of the USB are especially useful for a motor control system:

- Packets with a maximum size of 1 kByte are transmitted at a 1 kHz bus clock rate for high–speed devices. This is sufficient for high–level control of most industrial motors.

- The bus uses a fixed time–out–period of 1.5 μsec. A spurious transaction therefore does not block the bus for more than the transaction–time and the time–out–period.

- The USB is a deterministic bus with fixed time–out–periods and synchronized frames. Hence, worst–case bus load and communication dead time can be precalculated.

- The USB specification provides several error detection mechanisms for both the client and server side. This includes the detection of transmission errors, loss of frame synchronization, and attachment / removal of devices. Once an error is detected, an appropriate error handling procedure, e.g. the emergency stop of the robot, can be invoked.

Data transfer via USB is in general lossless. The USB specification 1.1 defines four basic transmission types [13]:

- *Control transfer* (bidirectional) for configuration and other device specific purposes

- *Isochronous transfer* (unidirectional) for streaming real time data like live voice and video sequences (not lossless)

- *Interrupt transfer* (to Host) for small amounts of data for continuous or event oriented transfer

- *Bulk transfer* (unidirectional) for large amounts of data with wide dynamic latitude in transmission constraints

In the case of the wheel system, each motor controller is accessed by a *bidirectional control channel* and an *unidirectional interrupt channel*. The *bidirectional control channel* is used to initially configure the microcontroller board and to continuously transmit desired velocity values from host to motor controller. The unidirectional interrupt channel is used to transmit the actual motor position, motor velocity, and wheel system status to the host. Both channels operate at a 1 kHz rate.

In our implementation, the high speed USB client controller USBN9602 by National Semiconductors [19] is used.

4 Conclusions and Future Work

A family of modular all–in–one wheel systems for combined steering and driving has been introduced, which are based on standard tires. They are very compact and provide a high carrying capacity with a low dead load. A prototype implementation has been presented, which can be used as a plug–and–play building block for a variety of highly maneuverable mobile robots. The wheel offsets can be chosen arbitrarily in both the lateral and the longitudinal direction, so that omnidirectional and even fully holonomic mobile robots can be configured.

The wheel system is already equipped with the necessary power electronics and low–level controllers. Communication to the host computer is done via the universal serial bus (USB), which provides the desired real–time capabilities and is a standard interface used with every PC and many consumer products.

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