ParcelBot: A Tracked Parcel Transporter with High Obstacle Negotiation Capabilities

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This paper introduces ParcelBot, a tracked robot designed as an assistance device for packet delivery services. Its application field requires high mobility in an artificial environment, including the ability to overcome fairly large obstacles such as stairs. The platform is moving on tracks but consists of a mechanism to tilt the robot, so that it behaves like a wheeled system. Compared to pure tracked or wheeled robots, the combination leads to an increased obstacle climbing ability, superior maneuverability and higher energy efficiency due to less friction losses when navigating on flat ground. The paper focuses on the mechanical design of the prototype and highlights a selected number of experiments.

1. Introduction

The prototype, that is presented in this paper, was designed for the following application scenario: It is intended to serve as a human operated transporter for parcel delivery services, capable of carrying significant payload from a delivery car to the end customer. This scenario imposes that the robot has to be able to climb up artificial obstacles, typically stairs and has to be able to navigate on them robustly and with sufficient speed. The operation in a human defined environment on a very specific task clearly restricted the design choices. The size of the robot was influenced through specifications of the parcel delivery services (payload dimensions and weight), but also by the local building law and official recommendations from the council for accident prevention (stairs step height, width and inclination, [?]). While many existing robots partially full-filled the
imposed requirements (such as [?], [?], [?], [?], [?], [?]), none of them seemed to be ideal for our specific scenario. Some of the existing platforms did not feature the required obstacle negotiation abilities, some were not able to handle sufficient payload and others were not applicable due to the need of elaborate perception to allow for robust locomotion. Hence we needed to develop a novel system that masters these specifications in a single device. This paper introduces the hardware prototype and mainly focuses on the mechanical design and its evaluation, while the electronic setup as well as the control software are just roughly enlightened.

2. Obstacle climbing method

Due to the requirement to be able to navigate on stairs, the robotic platform has been designed as a tracked vehicle. Since the tracks alone (without a massive track height) did not provide the needed obstacle climbing abilities, an additional mechanism had to be incorporated. It consists of a lever arm with two passive castor wheels. While the arm is stowed in the main body, the robot behaves as a common tracked vehicle. With deployed arm (see Fig. 1, a), the ParcelBot acts like a purely wheeled system. This configuration is applied to move on flat ground and allows to navigate with less slippage which results in a higher turning rate, less friction losses and also reduced abrasion of the floor/tracks, that is important when performing on private stairways. The arm is as well used to lift the robot onto the obstacles. The process of stair climbing is illustrated in Fig. 1. While the robot approaches the obstacle, the lever arm is deployed. Once the tips of the tracks are on the obstacle, the lever arm is inserted into the main body. From then on, the robot takes advantage of the tracks to move on the stairs. At the end of the stairway, the robot stops its forward motion and deploys the lever arm again to quit the obstacle.

2.1. Mechanical design

The actuation unit for the tracks consists of a motor (Maxon EC 60, 400 W), a planetary gearbox (Maxon GP 81, reduction rate of 25:1) and a shaft extension and coupling system (Fig. 2). An in-track design has been chosen, which means that all parts required for the track actuation were embedded inside of the track unit. This holds for the mechanics, but also for the motor control electronics. Beside a simple mechanical mount, only electrical power and control signal connections have to be made to actuate the track. This largely simplifies the usage as well as the protection and
Fig. 1. a) Concept of the ParcelBot, a tracked platform that can be inclined by a wheeled lever arm. In the inclined configuration, the robot behaves on flat ground like a purely wheeled system. b) shows an illustration of the stair climbing process.

Fig. 2. CAD image of the actuation system of the tracks. a) shows drawings of the generic shaft extension and coupling unit and its integration into the track unit. b) illustrates the complete robot with the main body and the left and right track units.

sealing. The torque requirements and therefore the motor/gear combination for the track actuation has been defined based on two operating cases and on the payload and system specifications (Table 1): In the nominal case, both tracks of the robot are in contact with the stairs with inclinations up to 35 degrees. In the worst case scenario, only one track is in operation. The torque requirements were calculated to be 27 Nm (8 Nm on flat terrain) for the nominal case and 36 Nm (11 Nm on flat terrain) for the peak load. Based on that, the gear ratio has been determined to be 25:1 for the planetary gear and 2:1 for the bevel gear inside the coupling system. This resulted in a continuous torque of 26.6 Nm and peak torques of approx. 35 Nm with drive speeds of up to 0.5 m/s.

Another design focus was made on modular and reusable mechanical parts. Therefore the same actuation unit could be used for the lever arm mechanism by just mounting a different planetary gearbox. The lever arm was one of the most critical elements of the mechanical design of the robot (Fig. 3). Since it has to incline the fully loaded robot and to sustain significant impact collisions (e.g. during the training phase of the operator), it
was designed powerful and robust. A performed FEM analysis on selected parts with static forces (up to 1000 N) and impact forces of up to 3000 N confirmed the robustness of the lever arm (Fig. 3, a). Beside these considerations, the dimensions and mounting position, which strongly influence the stability on obstacles, were carefully defined. The high torque requirements of the lever arm mechanism were satisfied by choosing a reduction rate of 308:1 of the planetary gear, while the bevel gear ratio remained at 2:1. This resulted in a continuous torque of approx. 240 Nm and peak torques of up to about 310 Nm, with a turning rate of around 12 degrees/s. The tip of the lever arm was equipped with two castor wheels. During the deployment and the suspension of the arm, the steering axis of the castor wheels had to be blocked. A clutch has been developed that can actively be released by a servo motor.

The design of the main body of the robot was kept very simple. It consisted of a robust mechanical structure to connect the two track modules with the lever arm and a box to store the electronics including power converters, signal converters, and computers.

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<tr>
<th>Key data of ParcelBot</th>
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<tr>
<td>total length</td>
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<td>total width</td>
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<td>total height</td>
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<td>total mass</td>
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<td>max. tested payload</td>
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<td>max. slope angle</td>
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<td>per track: Cont. torque:</td>
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<td>per track: Max. torque:</td>
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<td>lever arm: Cont. torque:</td>
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<td>lever arm: Max. torque:</td>
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<td>max. forward velocity:</td>
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3. Control overview

Due to the teleoperation of the robot, a simple control scheme could be selected. Fig. 4 shows a block-diagram of the different electrical components involved to control the robot and the data-flow from the operator to the robot. As a user interface, a gaming controller (Nintendo Wii remote) has been applied. This allows an operator to input commands, but also to receive feedback from the robot via LEDs and sound output. The remote control is used to set the reference velocities of the robot body (the translational velocity $v_B$ and the rotational velocity $\omega_B$), as well as the joint angle of the lever arm $\phi_C$ and a signal $f_c$ to enable or disable the clutch to block the rotational movement of the two castor wheels. The commands are sent via Bluetooth to the on-board PC (ASUS EEE PC) of the ParcelBot. The on-board computer calculates the reference turning speed $\omega_R$ and $\omega_L$ of the right and left driving motors based on a differential drive kinematic model of the robot:

$$\omega_R = \frac{v_B + \frac{1}{2} \omega_B D}{R_R} \quad \omega_L = \frac{v_B - \frac{1}{2} \omega_B D}{R_L}$$

$D$ denotes the distance between the centers of the two tracks and $\omega_B$ the rotational velocity around the center of the robot respectively the center of the back axis, if the robot is in its inclined configuration. $R_L$ and $R_R$ stand for the radius of the left and right driving wheels (resp. the track height) that actuate the tracks. The reference motor signals are sent over CAN to the motor controllers (Maxon EPOS 70/10), that executed the velocity control loops for the track actuation and a position control loop for the lever arm actuation.

The clutches are operated by sending PWM signals to their actuators (Standard Servo Motors). To generate the signals, a custom made microprocessor board (with a Microchip dsPIC33) is used. The signal to enable/disable the clutch is sent by the on-board PC via serial connection.
Fig. 5. Pictures of the robot deploying the lever arm (a) and climbing up the first steps of a stair (b). c) illustrates the navigation capabilities on stairs (as overlay of images).

4. Experiments

The manufactured prototype was tested in different experiments. To characterize the locomotion performance, turn-on-spot maneuvers in normal and inclined configuration, obstacle climbing and navigation experiments on stairs have been executed. Fig. 4 a, shows a sequence of pictures of the inclination process, while b depicts the stair climbing process. Fig. 4 c contains a sequence of picture of the robot while navigating on the stairs. The robot successfully climbed up and down step obstacles with heights of up to 30 cm. For the stair climbing maneuvers, the geometrical properties of the first step were most critical. Stairs with a comparably low first step led to a low inclination angle of the robot and made it more difficult to climb on the second step (Fig. 4, b). This difficulty was already identified in the design process and did not affect the performance of the robot in the selected experiments. In contrast, the experiments illustrated that the tracks of the robot were not ideal for the navigation on steep stairways with rather slippery material properties. Conveyor belts have been used as tracks for the first prototype. Those belts where rather stiff with a low coefficient of friction and therefore increased the slippage of the robot. Using custom made tracks with appropriate material properties and grouser shapes would have reduced the slip effects. Nevertheless, navigation on common concrete stairs was easily possible (Fig. 4, c).

5. Discussion

While many existing platforms seemed to have been suited for the given application, every compared system showed certain drawbacks related to the task. Conventional tracked robots ([?]) usually require a track height in the range of the double step obstacle height to climb on and don’t allow
smooth transitions on the stairs. Tracked systems with flippers or other suspension mechanisms ([?],[?],[?]) would have been appropriate for smooth stair climbing but locomotion on flat ground would result in higher friction losses than for wheeled systems. Wheeled climbing robots, such as the Shrimp ([?]) or the Octopus ([?]) possess high obstacle climbing capabilities, but their performance on stairs strongly depends on the step properties (mainly on the step height and step length) and robust navigation on the stairs becomes very hard. Our platform combines the advantages of tracked and wheeled systems. In the nominal configuration, it behaves like a ordinary tracked robot, in inclined configuration rather like a wheeled system. This helps to reduce the friction losses for motion on flat ground and increases the robustness for navigation on stairs. The lever arm also support the obstacle climbing process by allowing to lift the robot onto the obstacles.

While the payload ratio of about 0.25 is rather low for such a system, there is still room for improvement (it has to be mentioned that the payload ratio of 0.25 does not reflect the effective payload capabilities of the robot but rather what has been specified and tested in the climbing experiments. Driving on flat ground was tested with a payload of 80 kg). The mechanical structure is build very rigid with high safety factors. Optimizing the ratio of payload was not part of the study and should be addressed in a next design iteration.

Heading towards a real application, certain additional features would be beneficial. First, the level of autonomy would have to be increased. The teleoperation of the robot was sufficient for a preliminary study, but of course, it would be desirable to disburden or even forgo an operator. Further, an additional mechanism to shift the position of the payload (and
therefore the center of gravity or the robot) during run-time would help to
increase the robustness of the system on steep obstacles and in our case,
would lower the constraints that are posed on the payload location to allow
for smooth obstacle climbing without tilting e.g. when leaving stairways.

6. Conclusions
Various specifications and requirements given by the concrete application
largely restricted some of the design choices. The others as locomotion
method or actuation principles were to be selected. The choice of using a
tracked vehicle with a deployable castor wheel mechanism proved to be very
qualified for the task. The design and assembly process could be simplified
by constructing the track modules as independent units with a simple in-
terface to the main body and by designing a generic motor module. This
module was applied to actuate the tracks with torques of around 25 Nm
and, with just simple changes, the lever arm requiring torques of up to 300
Nm. Experiments demonstrated that the robot successfully performed in
simple application scenarios. The teleoperation of the robot by a roughly
skilled operator lead to a smooth obstacle climbing maneuver.