Mechanical Design of a Rover for Mobile Manipulation in Uneven Terrain in the Context of the SpaceBot Cup


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Abstract

This paper describes the development and test of a mobile manipulation platform intended for a terrestrial robotic competition. While current space missions are planned to minimize complex manipulation tasks, plans for future space missions go beyond these restrictions. Infrastructure deployment, human-robot cooperative missions and complex sample collection require increasingly complex manipulation capabilities. To meet this need the Spacebot Cup consists of several complex manipulation tasks in unstructured terrain. These requirements were the main design driver for the presented system. The presented rover consists of a 3-Boogie-Chasis designed to increase the maximum stepping size, flexible rubber wheels to increase the maximal climbing inclination on loose surfaces and a small six degree of freedom manipulator to handle objects within the competition. The iterative simulation and experiment process used to develop the flexible rubber wheels is presented. Furthermore experiments are presented which allow a performance comparison between flexible and rigid wheels on loose surfaces.

1 Introduction

The SpaceBot Cup announced in December 2012 by the DLR had the goal of transferring knowledge from other disciplines to the space sciences and vice versa. The SpaceBot Cup is a robotic competition mimicking an extraterrestrial exploration scenario regarding communications delay, operation, and ground surfaces. The DFKI team ARTEMIS (Autonomous Rover Team for Exploration and Manipulation Intended for SpaceBot) took part in the SpaceBot Cup while the system described in this paper served as autonomous exploration rover.

1.1 Mission Scenario

Within the competition the system had to autonomously explore a 29 m x 22 m terrain, starting at a previously defined lander position. GPS was unavailable for navigation and localisation. Furthermore, the detection of the system state was possible only via onboard sensors. The robot had to find and identify three different objects of known size and color, then grasp two of these objects and transport them to a base station (third object) where they were to be assembled. The main parts of the competition were:

- Mapping of the area
- Localisation of the rover in the map
- Localisation of mobile and fixed objects
- Moving on unstructured surfaces covered with fine-grained soil and gravel
- Collection of the mobile objects
- Assembly of the mobile and fixed objects
- Drive back to the landing site

These tasks had to be done in one hour. Including three checkpoints within the "groundcrew" could interact with the system for five minutes. All communication was effected with a latency of two seconds.

1.2 Requirements

The overall system mass was limited to 100 kg including additional communication devices at the lander site. The number of robots used to solve each task was not subject to regulations and the type of locomotion was left to each groups discretion. The system had to be able to manipulate two different mobile objects: a cup-like object with a diameter of eighty millimeters and mass of 600 g and a "battery" pack with dimensions of 200 mm x 40 mm x 100 mm and mass of 800 g. The inclinations...
on the competition site were between 15° and 30°. While the 15° slope had to be overcome to complete all mission tasks, the 30° slope was optional, constituting the shortest route.

2 Mechatronic Design

The mechatronic design was directly driven by the mission requirements described in the introduction. To create such a system in under eight months the decision was made to use existing subsystems and components designed in other projects. Apart from the reused adapted subsystems, elastic wheels and a robotic gripper were developed from scratch.

Concept Initial concepts consisted of two heterogeneous robots which were to solve the tasks cooperatively. However, it soon became clear that such a multi-robot system would be too expensive to design to a high reliability. Due to the short time frame this concept was inappropriate, so a single robot system was developed (Fig.1). To meet the contest requirements the system had to provide three major hardware characteristics: a proper sensor concept for proprioception and exteroception, a chassis capable of overcoming uneven terrain and the ability to manipulate the objects. The final system, including the base station has a weight of 87 kg. The rover itself has a size of 830 mm x 1300 mm x 500 mm (width x length x height). It is equipped with a six degree of freedom manipulator and is able to operate over one hour without external energy.

Components To solve all the contest tasks a variety of sensors and support devices were intended. The most important are depicted in Figure 1. Mounted on top of a sensor mast is a Velodyne HDL-32E LiDAR sensor to map the whole area. Three ATV Prosilica enable the system to perform colour based object detection. To provide acceleration, velocity and orientation an XSens MTi-30 AHRS IMU is mounted under the three main cameras. This position was chosen because it is as far as possible away from all strong electromagnetic fields created in inductors such as motors and power supplies. To process all sensor data and planning tasks an Intel Core i7 embedded PC (KTQM77) is integrated. In order to avoid collisions the system is additionally equipped with two laser scanners (Hokuyo UTM-30LX). They are mounted in the front and rear of the chassis on a servo driven tilt unit. While the manipulator handles objects the forces between gripper and manipulator-arm are sensed by an ATI force-torque sensor (Mini45). The communication with the base station is realized over a 5.8 GHz 802.11ac WLAN connection. See [1] for more information on the software and autonomy aspects of the system.

2.1 Manipulator

The manipulation device is one of the integral components to solving the given contest tasks. The developed manipulator consist of six actuators with BLDC2 motors from RoboDrive and Harmonic Drive transmissions with a reduction ratio 1:100 [2]. In order to adapt to development time all six actuators are identical. This increases the weight to payload ratio due to the heavy actuators near the end effector. To cope with this drawback a support spring is attached between the second and third actuator (Fig.2).

Figure 1. The Rover with all subsystems and the objects to be manipulated, battery (yellow), cup (blue) and basestation (red) [CAD drawing]

Figure 2. Manipulator with spring support

If the manipulator is in a vertical position the spring doesn’t affect the manipulator. In a horizontal posture the spring provided 284 N of support, producing 17.6 N m torque. The additional weight caused by the springs is about 130 g. The springs reduces the load for the first actuator roughly about 40% (Fig.3). The depicted current for

2Brushless direct current
the first actuator results from a transition from the vertical into horizontal posture. The nominal torque of the actuators is 28 N·m with a maximum angular speed of 55 rpm. A single actuator weighs 525 g which results in a weight to torque ratio of 0.02 kg/Nm. The whole manipulator with gripper has a weight of 4.25 kg and can lift a 1 kg payload.

2.2 Flexible wheels

The static stability of the platform and the traction force between ground and wheel surface are important parameters for locomotion on uneven terrain. To increase the traction the contact area between ground and wheel can be enlarged by increasing the wheel diameter or via flattening the wheels [3] [4]. This approach is common in space applications where it is implemented with flexible metal wheels. However, a major disadvantage of this approach is the poor performance observed on rigid surfaces due to the low friction coefficient of metal on hard surfaces.

To improve traction an to simplify manufacturing, elastic rubber wheels were developed. Each wheel is made of three disks of water jet cut EPDM (Ethylene-Propylene-Diene-Monomer) with a thickness of 30 mm. These layers were adhesively bonded with elastic materials superglue (LOCTITE™480). The first design (Fig.5a) was developed without the help of simulation by using an "educated guess" approach for the evaluation of different spring-element shapes.

Unfortunately, tests have shown that the required forces for the desired deflection cannot easily be predicted by estimation. For a deflection of 15 mm, a Load of ≈1000 N, while the given force is ≈165 N (Fig.6).
For the next design iteration, a contact body FEM simulation was used to predict mechanical properties. To reduce the simulation complexity, the model was simplified to a two-dimensional setup using Tria 6 Elements. A Mooney-Rivlin-Model based on uniaxial, planar shear and simple shear experimental data was used to simulate the elastomer material properties. The simulation results were evaluated using the prototype test of the first design model and show an adequate approximation of the test results. With the simulation model, a variety of shapes and wall thicknesses were analyzed until a combination that results in a deflection of 17 mm for the given load was found. The final design (Fig.5b) shows roughly linear behavior within the expected operating range. Final tests with the rover have proven the correctness of the given assumptions.

2.3 Suspension System

The locomotion platform is realized as a 3-Bogie passive suspension to compensate unevenness of the terrain. The 3-Bogie concept was originally proposed for the ExoMars rover [5] and it was also used to build the mobile platform for AILA [6]. The main characteristics of this concept are the lower mass and higher or equal static stability compared with other concepts like the CRAB, RCL-E, and the Rocker Bogie [7]. This high static stability is advantageous for mounting the laser scanner at a proper height to provide a maximum field of view over robot and adjacent environment. Each bogie is equipped with two active driven wheel units for steering and to drive the adaptive wheel. This enables the rover to drive in every direction with any orientation for the whole system. This allows for much easier and precise positioning with regards to objects which are to be manipulated. The wheel is mounted off-axis to the active driven steering axis. For reasons of efficiency this axis is held by an electro-magnetic brake. The whole design enables the adaption of different wheels in diameter and width. An additional effect of this design is also that the wheel supports rotations of the steering axis. The rockers are passive while in the setup and can be adjusted by limiting their rotation angle. The decision of the limitation depends on the wheel size and ground condition to lift the chassis before ground contact. These parameters were determined with stepping-over tests. Each bogie is equipped with an absolute encoder to determine the current position.

3 Experiments

Several experiments were conducted in order to evaluate components within the locomotion unit. The main focus of these was the evaluation of the passive suspension and flexible wheels.

3.1 Step Climbing

Besides static stability, the maximum height of conquerable steps is a significant indicator for the quality of mobility in unstructured terrain. This value was obtained for both the flexible and the rigid wheels. These revealed that the system is able to overcome steps 320 mm high with both wheels (Fig.7). This is one and a half times the

![Figure 6. Flexible wheel deflection and forces](image)

![Figure 7. Step test with flexible wheels](image)
wheel diameter. State-of-the-art passive suspension units allow the system overcome obstacle with double the wheel diameter [8]. However the results are not directly comparable due to influencing factors such as scalability, differences in sensor and component configurations as well as overall mass and dimensions of the system.

3.2 Static Stability

To overcome steps with the system as well as to drive in steep inclinations a high static stability is advantageous for the system. Other than designing with consideration in regards to static stability, tests were required to ascertain the actual static stability of the final system. This test is necessary on account of differences between CAD models and the actual system (Fig.8).

![Static stability longitudinal](image1)
(a) Static stability longitudinal

![Static stability transversal](image2)
(b) Static stability transversal

**Figure 8.** Static stability test of the whole system

The system offers a static stability at the longitudinal and transversal side of more than 45°.

3.3 Wheel Test

To evaluate the flexible wheels the system was tested on loose glass sand with a grain size of 1-3 mm diameter. This was done on a sand box with adjustable inclination (Fig.9).

![Setup for slip experiments](image3)

**Figure 9.** Setup for slip experiments

The flexible wheels were compared with rigid wheels of the same effective diameter hence the distance from the wheel axis is the same for the flattened flexible wheel and the rigid one. The results are depicted in Figure 10 for 0° to 15° inclinations.

![Comparison between rigid and flexible wheels with 0° slope](image4)
(a) Comparison between rigid and flexible wheels with 0° slope

![Comparison between rigid and flexible wheels with 10° slope](image5)
(b) Comparison between rigid and flexible wheels with 10° slope

![Comparison between rigid and flexible wheels with 15° slope](image6)
(c) Comparison between rigid and flexible wheels with 15° slope

**Figure 10.** Slip experiments for elastic and rigid wheel

The position of the rover was tracked with a Qualisis motion tracking system. As a reference the rover was programmed to drive 2 m straight ahead with a velocity of 0.1 m/s. A slight variation to the reverence time of 20 s for each run could be explained by the control error of the wheel speed controller. The red lines represent the rigid wheels and the blue ones the flexible ones. The error bars represent the variance of the measured values re-
lating to the mean value. The errors within the test on 10° inclination are conspicuous, overall however the rigid wheels performed better than expected. Tests had to be repeated with a higher number of experiments. These revealed that the rover performed significantly better on all inclinations when fitted with the rubber wheels. The improvement ranged from 16% at 0° inclination up to 214% at 15° inclination. About 15% inclination the performance of rigid wheels was so bad they were no longer comparable with the flexible wheels. In order to paint a clearer picture experiments using the flexible wheels were continued until performance deteriorated to more than 90% slippage (Fig.11). Even at 20° inclination the rover moved forward. For a complete system with sensor, manipulation abilities and storage facilities for the objects to be handled the performance was adequate and allowed the robot to overcome any inclination or loose surface within the competition.

4 Conclusion and Future Work

The paper presents the development of a mobile manipulation platform including a six DOF manipulator, flexible wheels and a 3-bogie chassis. Furthermore experiments are presented evaluating the performance of the chassis and flexible wheels on loose surfaces. The chosen design results in a high static stability and climbing capabilities of one and a half times wheel diameter. The flexible rubber wheels performed better than rigid wheels of the same effective diameter at any inclination. The maximum inclination on loose glass sand showed an increase from 15° with rigid wheels up to 20° with the flexible rubber wheels. These flexible wheels are not intended for space application and function as more of a transfer technology for terrestrial robotic applications. While the Tweels™ developed by Michelin are designed to replace conventional air tires with the advantage of higher reliability, our flexible wheels are developed to provide a higher contact patch between the contact surface and the wheel in order to gain higher traction on loose surfaces. These flexible wheels could be useful for robots in disaster areas and other unstructured terrain. Future development will consist of a investigation of different material combinations, shape variations and comprehensive tests.

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