Ackerman Steering Chassis with Independently Driven Back Wheels

Tomáš Ripel
Brno University of Technology
Faculty of Mechanical Engineering
Brno, Czech Republic
tripel@centrum.cz

Jan Hrbáček
Brno University of Technology
Faculty of Mechanical Engineering
Brno, Czech Republic
jan@hrbacek.info

Jiří Krejsa
Brno University of Technology
Faculty of Mechanical Engineering
Brno, Czech Republic
krejsa@fme.vutbr.cz

Abstract— **When building the robot for outdoor competition the designer can choose from a variety of chassis. The differential drive and Ackerman steering drive are among the most popular. The paper describes our experiences with the custom built chassis that uses Ackerman steering principle together with independently driven back wheels. The chassis represent the base of Bender II mobile robot, used in Robotour 2009 outdoor competition. The goal of such solution is to obtain better traction on rough outdoor surfaces while keeping the mechanical design simple.**

Mobile robot, chassis concept, software differential

I. Introduction

Mobile robots can be seen more and more often these days. And not only the sophisticated scientific instruments, such as the Spirit and Opportunity rovers, that are moving on the surface of Mars since 2004. It is only a matter of time when autonomous robots become an ordinary part of our lives. Robotic contests play important role in speeding up the development of reliable robots both regarding the mechanical/electrical components and sophisticated control and navigation algorithms. Robotour competition is one such contest that enables smaller robots to compete, thus bringing into the design process the student teams.

The design of autonomous mobile vehicle is a sophisticated task to solve and construction of mechanical parts belongs among the most important parts the design stage. The selection of the type of the chassis used in the robot is the essential in the whole construction concept. This paper describes the approach used in Bender II mobile robot, used in Robotour 2007 and 2009 competitions. Bender II was designed mostly by the bachelor students.

Several chassis concepts are suitable for mobile robots [1] and many aspects have to be considered during its selection. Among the most important issues we can count robot utilization, energy convenience and environment, where the robot operates. Differential drive system [3] is the most common for its good maneuverability and it´s also very suitable for terrain irregularities. It´s construction is simple. However in case of more than two driven wheels configuration appears troubles caused by slippage wheels on the surface during wheeling, therefore the main disadvantage is its low efficiency. That leads to necessity to overdesign the actuators. The omnidirectional chassis has more efficient motion, but there are still huge losses from friction caused by fact, that not all wheels rotate in the direction of movement. It also requires flat and hard surface with no obstacles for its optimal utilization. The biggest advantage of omnidirectional type of chassis is ability to move holonomically which means that it can instantaneously change direction. This is utilized by wheels construction which has many varieties such as roller [4,5], Mecanum [6,7] or spherical wheels [8,9] are. Hybrid chassis with an independent rotation of all wheels behaves very well in uneven terrain, but because all wheels have to be powered and driven separately, it´s very inconvenient from the energetic point of view and also complicated to control.

Ackerman chassis is the most common type used especially in automotive industry, where it represents major share of applied chassis. This concept provides very efficient motion which is for mobile robots essential. The remaining issue is the possible loss of traction when mechanical differential is used. This paper describes our modification of classical Ackerman chassis in order to keep its advantages and resolve the drawbacks.

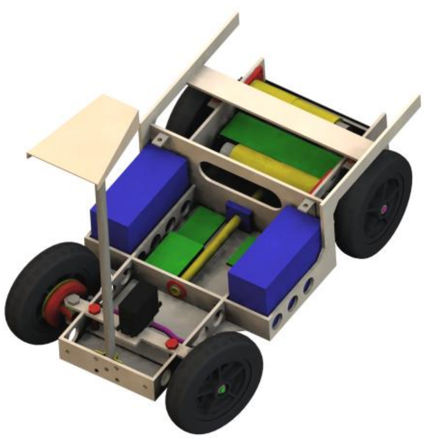

Figure 1. Bender II mobile robot 3D model

II. THE CHASSIS CONCEPT

Bender II is a four-wheeled mobile robot of medium size. It was designed as a testing platform for fusion of sensors and for robotic outdoor competitions at the Institute of Solid Mechanics, Mechatronics and Biomechanics, Faculty of Mechanical Engineering, Brno University of Technology. Platform total weight is 25 kg, and payload is 7 kg. It´s 600 mm long and 300 mm wide with 50 mm road clearance. Wheels are inflatable of 160 mm diameter. The robot was first modeled in SolidWorks, see the 3D CAD model in Figure 1.

In Bender II chassis the Ackermann steering is combined with independent rear drives. The concept of Ackerman steering was chosen as an effort to design mechanical platform comparable with real vehicle, while the independent rear drives were proposed to improve the traction in uneven surfaces the robot was aimed to operate in. Although the whole construction is simplified by the absence of suspension, robot´s behavior is similar to classical automobile motion. Because rear wheels are driven separately, there is no necessity to use mechanical differential. The function of mechanical differential is substituted by driving algorithm that controls individual motors in accordance with the steering angle of front wheels.

A. The swinging rear axle

The most significant mechanical change contrary to classical automotive chassis is the application of swinging axle. This solution partly compensates suspension and partly solves the problems with required loading capacity which would be problematic in irregular terrain using rigid chassis. Swinging axle is usually applied in trucks for its good mechanical characteristics. Due to this simple, practical and efficient mechanical concept the traction of rear wheels is ensured.

For its realization it is necessary to divide rear axle from the rest of frame. In this particular solution the whole frame is divided into two parts. The rear part contains the drive units and chain drives transmitting torsional moment to rear wheels. Front part represents the main construction, where all others components are placed. Those two parts are connected by torsional shaft which allows the parts to swing around each other. The swinging is mechanically limited so the maximal angle is about 10°. This way the constant contact between rear wheel and surface is ensured even in cases when the platform has to deal with heavy loads (laser scanner and other sensory equipment). Figure 2. shows how the swinging axle works.

Rear units which independently drive wheels are controlled by master control system. This system sets different velocities for each wheel during steering in dependence on actual angle a speed of robot. This way is absence of mechanical differential solved.

The drive units consists of Maxon RE40 DC motor with a 3 staged 43:1 planetary gearhead GP 42C. Chain transmission between drives and wheels has the ratio of 1.5:1. The motors are controlled by speed controllers, which were specially designed for the Bender II requirements. It communicates with the master computer via the shared RS-485 bus. The drive units together provide the power of 300W and maximal torque of 30Nm. The power supplies are represented by two lead-acid accumulators 12V/7 Ah. Their theoretical capacity is 168Wh.

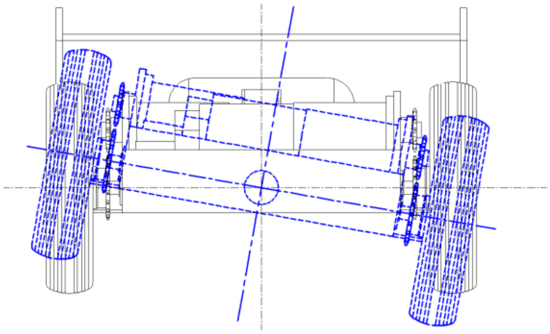

Figure 2. Swinging rear axle of the Bender II mobile robot

B. Ackermann streering

Ackermann steering (which is also known as kingpin steering) ensures proper angle of the front wheels during the robot wheeling. Each wheel has to be turned in a different angle, because each follows different radius. The inner wheel is tilted more, than the outer wheel. This condition is ensured by the geometry of the mechanism. This principle is useful especially at high speeds, because it reduces tire slippage. Although the Bender II is designed for slow speeds (up to 5km/h), the slippage effect (even infinitesimal) is undesirable because of the front incremental sensors. The steering mechanism is realized by double pivoting system. The pivots are at precise angles, so the imaginary axis passes the kingpin center, end of pivots and the center of rear axle (as shown on Fig. 3). The construction solution has to assure possibility to detent the static toe-in. This is realized by threaded rod.

These diagrams show how the Ackermann steering and swinging axle works. The pivot on Fig. 3 is placed in the center of the front wheel which doesn´t correspond with reality. From construction point of view it is almost impossible to achieve this pivot´s placement. The Bender II front wheels center of rotation is placed 50 mm off the wheel center which influences required torque of drive unit operating the steering mechanism.

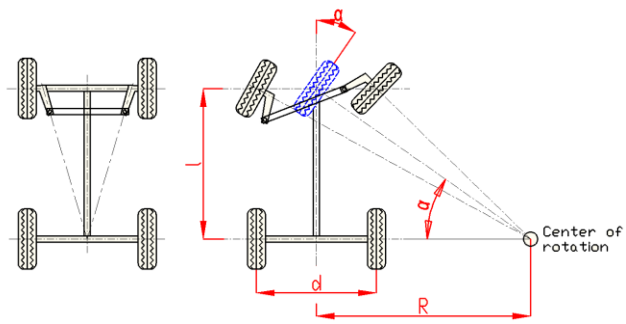

Figure 3. Ackermann steering principle

III. MECHANICAL DESIGN

The construction of robot chassis is a complex issue, which requires knowledge about its functions and purpose. Mechanical design of the robot Bender II is simple, robust and efficient. This chapter describes a solid construction of the main parts as frame, steering mechanism and rear swinging axle are.

A. Frame design

Optimal frame for mobile robot has to be rigid and lightweight at the same time, which can be assured by proper material selection and mechanical design. Bender II has welded aluminum frame divided into two parts. Both parts are assembled from aluminum bars and welded by TIG method. Front frame represents the main body of the robot. Its shape provides optimal placement of accumulators and other heavy parts (laser scanner) between axles. This concept ensures balanced loading to each axle, which is suitable for driving properties. However, little overload of the rear axle is desirable, because of better traction. Shape of the front frame is shown on Figure 4.

Figure 4. Front frame of the Bender II mobile robot

In the rear frame the drive units with controllers are attached. Canals in sidewalls ensure movable bearing of drive units to allow its shift in case of necessity to tense the chain. Axle driving shafts are embedded in the middle of rear frame in ball bearings.

Figure 5. Rear frame of the Bender II mobile robot

The frame is a slightly overdesigned. The bars it consists of have size 5x50 mm, which provides surface big enough to attach additional device in the case of need. To reduce the weight of mechanical construction the holes are drilled all over the frame.

B. Steering design

The mechanism of steering is controlled by actuator usually used in RC models. It has torque of 1.5Nm. Front axle has two parts. The lower part is closely connected with the frame and the upper part is connected with it by bolts. The body of half-axis is embedded between two axial ball bearings so it can rotate around steering knuckle. The rigidity of the steering mechanism can be controlled by the nut which is bonding upper front axis. As was already discussed in previous chapter the static toe-in can be controlled by threaded rod which connects draw rod with the body of half-axis. All parts of the steering mechanism are made from the steel for its durability.

C. Swinging axle design

The rear axle is connected to the front part by the shaft which allows swinging those parts relatively to each other. The shaft is actually a tube on which the radial ball bearings are pressed and it is fixed in the rear axle. Bearing housing is bolted in the front frame. The swinging shaft is embedded in the front frame and connected with it by retained ring. The main disadvantage of this mechanical solution is the fact that it longitudinally divides construction which makes difficulties with drive units bedding and space in the middle of robot. Swinging axle mechanism is easily demountable. The design of the swinging axle becomes clear on Fig. 6.

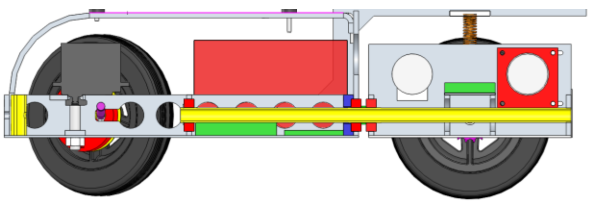

Figure 6. longitudinal cut through swinging axle

IV. SOFTWARE DIFFERENTIAL

Utilization of the software differential was mentioned in the previous chapter. Its algorithm controls independently the angular speeds of the driving motors and thus the rear wheels. The individual angular speeds of the wheels must be related with steering angle α. In order to determine the velocities, first the angular speed of virtual motor must be introduced, representing the movement of the robot:

$$\omega = \frac{v}{r} \cdot i \tag{1}$$

where v denotes forward speed, r is wheel radius and i is the total gear ratio between the motor and the wheel. The relation between the steering angle α and the curve radius R is illustrated on Fig. 3:

$$R = \frac{l}{\tan \alpha} \tag{2}$$

where l is the wheel base of the chassis. During the circular motion the dependence between tangential speed of a point and the distance to the center of the circle is linear. Such a distance, denoted R, is in the middle of rear axle, $R + d/2$ for the left wheel and $R - d/2$ for the right wheel (Figure 3). From this knowledge it is possible to express the relation between the tangential speed of left wheel and center of rear axle:

$$\frac{v_L}{v} = \frac{R + d/2}{R} \tag{3}$$

and similarly for the right wheel:

$$\frac{v_R}{v} = \frac{R - d/2}{R} \tag{4}$$

Tangential velocity is useful for good picture about robot´s speed, but for circular movement of wheel the angular speed is necessary. This is simply solved by multiplying the equations by v and i and dividing them by r. Final equations describe dependency between wheel spacing d and the current curve radius R:

$$\omega_L = \omega \cdot \left(1 + \frac{d}{2 \cdot R}\right) \qquad (5)$$

$$\omega_R = \omega \cdot \left(1 - \frac{d}{2 \cdot R}\right) \qquad (6)$$

where ω_L (ω_R) is the left (right) motor angular speed.

Quantities used in this paper follows a simple convention – turning to the right and forward movement implicates positive sign of the value, turning to the left and reversing is represented by negative sign.

A. *Implementation of the software differential*

The software architecture of the Bender II mobile robot follows a hierarchical scheme. The lowest level is formed by individual hardware devices, mostly interconnected by a shared RS-485 bus. The communication on the bus is controlled by a single master (the main computer) and makes use of a custom protocol. The exchanged data are encoded into packets of variable-length. The protocol features reliable delivery by using ACK/NACK response messages containing CRC consistency check result and automatic packet resending in case of ACK message timeout or NACK message reception.

The functionality of each hardware device is wrapped by appropriate low-level software module providing thread-safe access.

As a part of the middle-level software there is a module *Motion* that lies on the top of the low-level modules (individual hardware device interfaces). This module is an entry point for the higher software layers to control the motion of the robot. It encapsulates the software differential and provides two public methods – method `Go(speed, direction)` used to drive the robot at the desired speed to the desired direction and method `Stop()` equivalent to call `Go(0, anything)` to halt the robot.

The internal structure of the SW differential code follows the equations presented previously. The algorithm firstly converts the desired robot speed to the angular speed of a virtual centered motor. Then the desired curve radius according to (2) for a non-zero direction angle is computed (zero has the meaning of a straight movement and matches an infinite curve radius).

The next step is already to calculate the individual motor angular speeds according to (5) and (6). This can be done only when a non-infinite value of the curve radius is provided. Otherwise the differential algorithm is skipped and both wheels are driven at equal angular speeds.

The *Motion* module has now all the information to order the steering servomotor and the drive units to set the currently computed values. To conserve the shared communication bus bandwidth, *Motion* sends the command to each hardware unit only in case that the newly computed value differs from the previous one. The procedure described above repeats every time the upper software layers decide to change desired speed or direction of the movement.

V. HIGH LEVEL CONTROL

While the main aim of the paper is to describe the chassis, short description of the higher level control mechanism illustrate what structures were used during the competition. The overall scheme of high level control is shown on figure 7. Basically the action of the robot actuators must be selected properly based on all the sensory information, internal robot state, knowledge regarding the environment (no matter whether the knowledge is gained during the travel or inserted into the system prior to its mission) and goal definition. The actions are either in the form of general velocities – rotational and translational, that are further trasnferred depending on the type of the chasis; or actions are in the form directly linked to the chassis, in our case the steering angle and the translational velocity. Actions are further processed in the controllers, in Bender II case in the *Motion* module described in previous chapter.

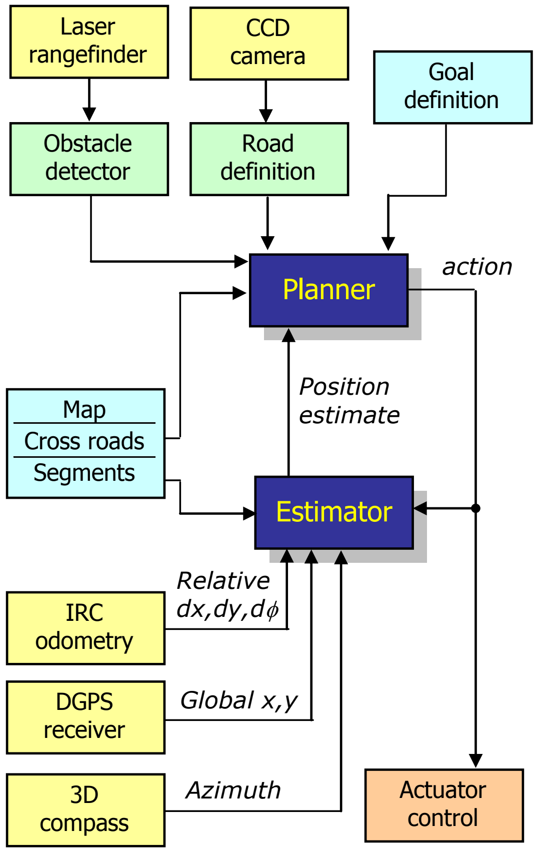

Figure 7. High level control scheme and signal flow

The action is produced by the planner based primarily on the sensory inputs and the estimate of robot position. The estimate is calculated by nonlinear version of Kalman filter. Some of the sensory inputs are fed into the estimator, processed and robots pose is extracted, while other sensory information are fed directly to the planner as the information from those sensors can not be used to determine robots pose, but are useful for planning. Lets first look at the estimator.

The estimator keeps the estimate of robots pose as an internal state. The state is changed by applying the action produced by the planner. Such a change is produced by the robot motion model. The information from IRC sensors on front wheels is used as an input to the motion model (even if strictly speaking such information is a measurement). The predicted state is further corrected using the measurements from sensor capable of giving the global position information.

In our case the xy coordinates are taken from the differential GPS receiver and heading angle is taken from 3D compass with the compensation of the mount plane inclination towards the ground plane. The particular sensor units used on Bender II were: as GPS receiver the custom built device based on the Lassen IQ module, digital compass module based on Honeywell HMC6343.

Estimator result is just one of the inputs to the planner. The main sensory input that keeps the robot on the path is the road description obtained from the processing of the images acquired by the camera mounted on the robot. Using preprocessing followed by the image segmentation and road description extraction the information about the local road is obtained and fed into the planner.

Image processing is not used for obstacle detection, the data from laser rangefinder by SICK is used instead. Such data are pre-processed by obstacle detector giving the planner information about avoidability of detected obstacle. Currently the USB2 Wide Angle Webcam Live WB-6200p is used, however the Pixelink family cameras are being tested as it provides high quality images mainly due to the high end optics.

The environment related information is used both in the estimator and the planner, the currently run segment of the map is extracted from the estimate while crossroad information are used by the planner. The goal of the whole mission is taken into account when globally planning the sequence of road segments taken from the environment map.

VI. EXPERIMENTAL EVALUATION

Robot Bender II has proved good behavior in both outdoor and indoor environment. Outdoor tests were performed on various surfaces like park footpaths, cobblestones and asphalt or sandy paths. During indoor tests robot has proved good mobility in spite of limited maneuverability given by the type of chassis selected.

A. Indoor test results

Very important test for mobile robot is its *power drain*. Bender II has a lot of electronic equipment on board which affects duration of its autonomous activity. This test was performed on flat surface with good traction properties. The TABLE I. contains the results of the test in different operational modes of robot. The term “on-board electronics” means the minimal configuration needed to drive the robot (drive controllers, steering control, wheel encoders, bus master unit and the main computer), not counting the power consumption of payload electronics.

TABLE I. ROBOT CONSUMPTION UNDER VARIOUS CONDITIONS

Regime of operation	***Average consumption [W]***
On-board electronics powered, no motion	33
Uniform motion at speed of 0.1 ms^{-1}	55
Uniform motion at speed of 0.2 ms^{-1}	60
Uniform motion at speed of 0.3 ms^{-1}	80
Uniform motion at speed of 0.3 ms^{-1}, 4° grade	120

On-board electronics of robot include beside basic electronics (approximately 33 W) also another major consumer, which is the SICK laser measurement scanner (LMS291). This device drains in operation roughly 30 W. With other equipment on-board like WiFi access point and the GPRS modem are, the total static consumption rises up to 70 W in average.

Another test performed on the robot was checking of stability. Good stability is necessary for its optimal behavior in terrain. The robot was tested with all possible equipment onboard because of its influence to the center of gravity. The test results confirmed this expectation; fully loaded chassis has very good stability for desired utilization.

More important than the static tests was dynamic stability trials. As was mentioned previously, the chassis has no dumping except the one provided by inflatable tires. Irregular terrain was simulated by obstacle (rectangular 4x8 cm cross-section) placed on flat floor. The height of the used obstacle determines theoretical maximal static tilt of the robot (i.e. vertical axis angular deviation when one front wheel is on the top of the obstacle) to value of 5.3°. The robot was overcoming the obstacle from different angles at various speeds and its response was observed. The result is that even in the case of the worst obstacle shape and position and relatively high speed, the fully loaded chassis embodies reasonable stability margin for reliable operation in target environments.

B. Outdoor tests results

This subsection describes robots behavior in outdoor environment for which it has been designed primarily.

Generally the one of the most important parameters for mobile robots is their *operating range*. The accumulators provide energy for all electronics onboard the robot including motors. Operating range is affected by consumption of each device. While robots movement is in non-traction mode, its energy demands are independent on running speed, from which we know, that the bigger speed the robot is moving, the bigger part of battery energy can be saved for traction. This fact was observed during the drive algorithms development. When at the beginning the speed was set to very low values (because of the safety reasons), the robot has reached the distance from start (without replacing batteries) of about 900meters. After speed increase to approximately 0.8 ms^{-1} the robot reached more than 1.6 km distance from the start. This value was found sufficient.

The traction was observed on a variety of outdoor surfaces during enormous number of tests, mostly in Lužánky city park, where Robotour 2009 competition took place. During the tests we did not encounter a single problem with the traction and independent rear wheel drives proved its advantages mainly on sandy surfaces.

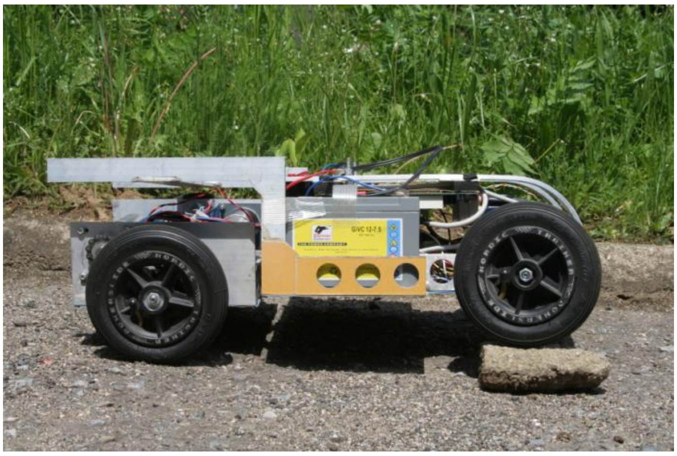

Figure 8. Swinging rear axle in action (side view)

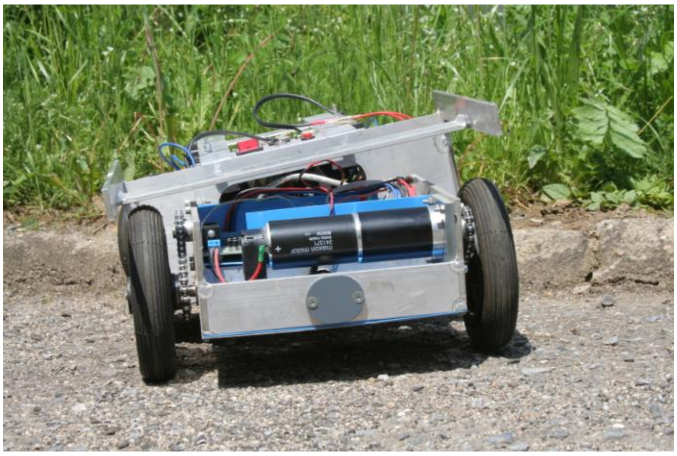

Figure 9. Swinging rear axle in action (rear view)

C. Overall experiences

It has been found that the chassis of our robot behaves well under various conditions. The independent rear wheel drives system does not suffer from the complete loss of traction in case of one wheel slippage, as both drive units hold their preset speeds independently. The swinging rear axle is capable of compensating terrain unevenness. By combination of these two major construction units, the robot is able to drive through surprisingly hard terrains and still behave well and economically on the road. Figures 8 and 9 show robots behavior in terrain.

While the ratio of the rear wheel angular speeds is dependent only on the steering angle and not on the unstable adhesion of individual wheels, the robot is not prone to under- or oversteering – the Ackermann steering is supported by the rear wheel speeds ratio.

The robot achieves forward speed of approximately 1 ms^{-1} (limited mainly by maximal input angular speed of the gearhead). Compared to an average light truck (that is likely to be robotized and autonomously operated in relatively near future e.g. in military supply service), our robot is scaled-down by factor of approximately 1:10. In this context, the speed of 1 ms^{-1} matches 10 ms^{-1} or 36 kmh^{-1} of a full-size vehicle. It may not seem to be very high, but the speed of an autonomous vehicle in an unknown and unpredictable terrain cannot be much higher in order to maintain both vehicle and environment safety. The only disadvantage of the presented independent drive units architecture (apart from obvious problems arising from using two motors, two gears and two controllers instead of one) is that the chassis becomes less controllable in case of misbehavior of one of the drive units. This happened at the beginning of the testing and was caused by communication problems, that be avoided by using a single controller driving both traction motors, when a possible communication failure would not cause discrepancy in wheel angular speeds.

VII. CONCLUCIONS

Autonomous mobile robot Bender II competed on Robotour 2007 in Prague and Robotour 2009 in Brno. The design of the robot, described in this paper in detail did not encounter any problem during the competition. The combination of Ackerman steering with independently driven back wheels and swinging rear axle exhibited outstanding behavior on a number of surfaces while keeping the energy consumption on acceptable levels. Therefore we can recommend this type of chassis to be used in robots designed for similar purposes.

The robot has been partially designed in the frame of several student projects. The students actively participated on the whole process beyond standard student´s work, resulting in higher motivation in further study process. The robot serves as educational tool for various tasks of dynamics, kinematics, electronics and data fusion.

ACKNOWLEDGMENT

Published results were acquired acquired with the support of the Ministry of Education, Youth and Sports of the Czech Republic, research plan MSM 0021630518 “Simulation modeling of mechatronic systems”.

REFERENCES

[1] R. Siegwart, I. Nourbakhsh, “Introduction to Autonomous Mobile Robots”, *MIT Press*, 2004

[2] H. Choset, et al., “Principles of Robot Motion", MIT Press, 2005.

[3] G. Campion, G. Bastin, B. d’Andrea-Novel, “Structural properties and classification of kinematic and dynamic models of wheeled mobile robots”, *IEEE Trans. Robot. Autom. 12*, pp.47-62, 1996.

[4] Fujisawa, S., Ohkubo, K., Yoshida, T., Satonaka, N., Shidama, Y., and Yamaura, H., “Improved Moving Properties of an Omnidirectional Vehicle Using Stepping Motor”, *Proc of the 36th Conf on Decision & Control. San Diego, California*, pp.3654-7, 1997.

[5] Williams, R., Carter, B., Gallina, P., and Rosati, G., “Wheeled Omni-directional Robot Dynamics Including Slip,” *Proc of 2002 ASME Design Engineering Technical Conferences*, Sep 2002.

[6] J. Salih, M. Rizon, S. Yaacob, A. Adom, M. Mamat, “Designing Omni-Directional Mobile Robot with Mecanum Wheel", *American Journal of Applied Sciences 3 (5)*, pp.1831-1835, 2006.

[7] Bradley A., Miller, S., Creary, G., Miller, N., Begley, M., Misch, N., “Mobius, an Omnidirectional Robot Utilizing Mecanum Wheels and Fuzzy Logic Control,” *Proc of the 28th Annual AAS Rocky Mountain Guidance and Control Conferences*, pp. 251-266, 2005.

[8] Ferriere L., Raucent B., “ROLLMOBS, a New Universal Wheel Concept,” *Proc of 1998 IEEE ICRA*, pp. 1877-82, May 1998.

[9] West, A.M., and Asada, H., “Design of Ball Wheel Mechanisms for Omnidirectional Vehicles with Full Mobility and Invariant Kinematics,” *ASME Journal of Mechanical Design*, 117, 1995.