Two-section Articulated Chassis with Active Articulating Joints and Walking Mechanisms for Enhancing Off-road Capability of Mobile Robotic Systems

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Abstract

Objectives: The relevance of this research is determined by challenges faced by today’s robotics and requirements regarding increased movement speed, enhanced mobility on rough terrain, with view to their limitations in weight and dimensions, increased operation time and range of coverage that are imposed on such devices. Therefore, this research aims at discovering a possibility of enhancing off-road capability of mobile high-mobility robotic systems. Method: Comparative analysis of a variety of chassis designs of high-mobility robotic platforms is the basic approach to studying this problem. This article includes a review of modern structures of mobility systems, and structural, configuration and specification advantages and disadvantages of such systems. Findings: An articulated chassis layout that includes active articulating joints with two sections and walking mechanisms was selected as a result of this research. Two mobile robotic platforms were developed according to this layout. Robotic platforms were tested and their high off-road capability was proved within this research. Test materials for one robotic platform and some simulation results for the other platform are presented in this article. Appearance is provided and the specifications of the developed mobile robotic platforms are given. Improvements: This article should be particularly interesting for designers of robotic mobility systems. This research reveals two modern high-mobility robotic systems that may be used for solving multi-objective problems in various industries.

Keywords: Articulated Frame, Mobile Robotics, Mobile Robotic Platforms, Mobility Systems, Off-Road Capability, Wheel-Walking Chassis

1. Introduction

Russian and foreign designers now pay great attention to development and exploration of high-mobility devices for ground use. Similar devices are developed globally in various industries and agriculture to explore hard-to-reach areas and for military purposes to run tasks that are beyond the functionality of available vehicles.

Mobility systems running on wheeled, wheel-walking, crawler and walking propulsion devices are used in modern high-mobility robotic systems.

A classical wheeled propulsion system is the simplest one of the listed propulsion devices and ensures steady movement in most road conditions; however, it falls behind all other devices in off-road conditions.

A crawler propulsion device has a great mobility on loose soils, but rather low obstacle passability and some disadvantages associated with track jamming, if any foreign object gets caught between the crawler elements and drive sprocket, which results in loss of mobility for two-track crawler mobility systems. The use of four to six-track mobility systems enhances obstacle passability.
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significantly, while also leading to an increase in mobility system mass and complexity.

To the contrary, a walking propulsion device has high obstacle passability; however, its mobility on loose soils is rather low. At the same time, mechanical structure and control system of the walking robotic systems are rather complicated, and the BigDog robot is an example of such complexity.

The use of wheel-walking mobility systems (chassis) allows for combining high obstacle passability and high mobility on the loose soils. At the moment, we can speak of several lines of the development of wheel-walking chassis structures for mobile robots. One includes such planet rovers as American Mars rovers Spirit, Opportunity, and Curiosity, Chinese lunar rover Jutu, and the prototypes of in-progress European Mars rover Exomars, which is developed with participation of Russian engineers (Figure 1).

All planet rovers and prototypes share the same body (container) and six-wheel chassis including a balance longitudinal lever suspension. These designs ensure steady movement across the soils with low bearing capacity due to application of the wheel-walking mode and overcoming the obstacles of height up to the wheel diameter, because the balance suspension ensures constant contact of all wheels with the soil.

A great variation of the wheel loads in ascends and descends is typical for the chassis with a single body. The difference in the wheel loads may be reduced by shifting the body with the help of the walking drives, e.g. when climbing a steep slope.

The chassis that use predominantly wheel mode for movement and walking for overcoming obstacles and movement across non-determined surfaces are another type of wheel-walking propulsion devices. Retiarius robotic platform (Figure 2) that can overcome complex obstacles can be referred to this category.

However, such propulsion systems are not capable of overcoming significantly high obstacles (approximately equaling to two wheel diameters) and have high mobility on the loose soils at the same time.

The use of articulated chassis allows not only reducing the dimensions of the mobile device, enhancing mobility on the loose soils, but also enhancing obstacle passability. Such structures may comprise three or two sections.

Three section chassis (Figure 3) have the highest mobility (both the obstacle passability and mobility on the loose soils), but at the same time an essential defect, i.e. three bodies (sections) of rather small volume for placing the payload. Two section chassis eliminate this defect, however, not completely.

2. Concept Headings

As electric motors, accumulators, and electronic equipment improves, a significant reduction in their weight and
dimensions is also observed, which, in its turn, facilitates reduced sizes and weight of control and power supply systems and gives the possibility to reduce dimensions of movement systems due to decreased volumes taken up by axillary and executive systems.

Therefore, on the one hand, decreased dimensions and weight of mobile systems are possible. However, on the other hand, road conditions and size of obstacles remain the same, and requirements are ever increasing to average movement speed up to (15-25 km/h), obstacle passability and mobility on the loose soils, operation time and range of modern mobile robotic systems.

Modern two-section articulated chassis allow for placement of the necessary axillary equipment in lesser space and the chassis mass is lower as well. However, a chassis that comprise an articulated framework ensure higher passability as compared to a single-body vehicle, due to the vehicle adaptation to the obstacles (ground relief). And with walking mechanisms added to the articulated framework and allowing for pulling in and out sections relative to each other, there is now a capability of overcoming the obstacles with height that exceeds wheel diameter.

For fixed obstacle size, we can talk about a possibility to reduce the vehicle size or about the increased obstacle performance of the vehicle.

This study aims at developing a new locomotion system design that comprises an articulated chassis and active articulating joints and walking mechanisms for mobile robotics of high mobility, manufacture of such chassis and their testing to compare with available analogues.

3. Results

A mobile robotic platform Mongoose-1 was developed in the STC “ROCAD”. It comprises two articulated sections, active articulating joints and two walking mechanisms that are installed in each section. The Mongoose-1 is equipped with six low-pressure wheels 145/70-6” (outer diameter - 350 mm). Chassis road clearance is 115 mm.

According to the tests, this chassis can overcome individual obstacles up to 100 mm high on the run, without any maneuvering (Figure 4).

Figure 4. Overcoming of individual separate obstacles up to 100 mm in height that does not involve any maneuvering.

For moving across a terrain with individual single obstacles with their height exceeding the road clearance, the chassis can overcome such obstacles by running the
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obstacle over with one of its side (Figure 5). Limiting height of such obstacles is 350 mm for the conditions of transverse chassis stability, which equals to wheel diameter.

Introduction of the active joints between the sections allows fixing the wheel drives directly on the sections with the wheels fixed rigidly to the output shafts of the wheel drives. The articulating section joints serve as the mechanical compensators, ensuring constant contact of all wheels with the ground (serving as a non-elastic balancing suspension). Simplicity, compactness, the absence of movable cables of the wheel drives and good cooling of the wheel drives are ensured.

Figure 5. Overcoming of an obstacle that exceeds chassis road clearance.

Introduction of the frame bend drive in the middle transversal joint and the walking drives leads to the increase of the passable obstacle height to over two wheel diameters when placing the wheels over the obstacle, controlling the section position on the obstacle (a reverse ‘bend’ of the load-bearing structure), movement across the loose soils, due to the possibility of individual axles shifting against the other axles fixed, and control of position of the center of mass.

Due to the articulated design, the chassis overcomes steadily the staircases with angle of ascent up to 30° (Figure 6). Availability of the walking drives allows changing the distance between chassis axles in order to adapt to the length and width of the stair step that is to be overcome. At the same time, an increase in wheel base due to walking drives, improves axle load distribution at the stair slope (Figure 7). Aside from the walking drives, the frame bend drive can also be used to overcome steep staircases and control the position of the center of mass, which allows for additional loading of two chassis axles by disengagement of the third axle.

The chassis is capable of overcoming solid slopes with the angle up to 40°, provided there is sufficient grip of wheels with the bearing surface. It is possible to overcome loose slopes with the angle up to 18° in the wheeled mode and in the wheel-walking mode up to 30° by axle-by-axle walking.

Overcoming of the escarps/counterescarps up to 250 mm in height can be done in a mode of free (passive) transversal joint of the middle axle. Both chassis sections rotate freely relative to each other in this mode around the transverse axis of the middle wheels, thus ensuring constant contact of all six wheels with the bearing surface, while overcoming the obstacles (Figure 8).

Figure 6. Overcoming a flight of stairs with angle of ascent of 30° (rise of staircase - 160 mm).
Figure 7. Overcoming a flight of stairs with angle of ascent of 35° (rise of staircase - 220 mm).

Figure 8. Overcoming an escarp of 250 mm in height with a free articulating link of the middle axle.

To overcome the escarps with their height over 250 mm, the articulating link of the middle axles is locked with the help of the output shaft of the framework bend drive, which ensured the possibility of forced turning of sections relative to each other at angle ±90°. By using walking drives and framework bend drive, the front-end chassis axle may be carried over the escarp that is up to 600 mm in height with further sequential carrying of the middle and front-end axles over the escarp (Figure 9).

Figure 9. Overcoming an escarp/counterescarp of 600 mm in height.

Figure 10 shows overcoming of an escarp of 600 mm in height and a wall that is located at angle of 45° and horizontal crushed stone platform in the mode of free articulating link of the middle axle and increased wheel base. Because of wheels of the front-end axle slipping on the crushed stone pavement, any further movement proved impossible. After the framework bend drive was turned on, the front wheels were loaded additionally by forced disengagement of wheels of the middle axle from the bearing surface, which helped with successful overcoming of the escarp (Figure 10, b).

Complex obstacles of various shape are overcome in a combined way, using passive self-adaptation of the chassis to the terrain relief and, if necessary, involving the frame bend drive and walking drives to re-configure the chassis on sections involving significant vertical obstacles.

Chassis transformation with the help of the walking drives and frame bend drive allows to overcome complex obstacles with the dimensions exceeding the wheel diameter, to move across the stairs with variable steps, to maneuver in the cramped space (narrow corridors, staircases etc.) and to take up minimum volume in transportation. Lifting of the sections gives a possibility to increase the height of positioning of the on-board surveillance devices and instrumentation.

Figure 10. Overcoming an escarp/counterescarp of 600 mm in height and a wall located at 45° and horizontal crushed-stone platform.
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Chassis configuration, involving maximum and minimum base, is given in Figure 11.

Figure 11. Chassis configuration, including minimum (a) and maximum (b) base.

Chassis configurations, including the front section rotated up at 90° and minimum and maximum wheel base of the front walking drive, are shown in Figure 12.

Development of mobile robotic systems with articulated chassis was continued with Mongoose-2 platform (Figure 13), which was developed as a part of an applied research under the support of the RF Ministry of Education and Science within the project 14.579.21.0127, unique identifier of applied research RFMEFI57915X127.

Figure 13. Mongoose-2 platform appearance.

Aside from the walking drives of the sections and frame bend drive, Mongoose-2 comprises section turning drives that are combined with the section walking drives in a single unit. These section turning drives ensure sections turning relative to their longitudinal axis (Figure 14). This gives additional advantages, enabling to:
- apply additional load onto individual wheels to generate the required propulsive effort on a certain wheel;
- give a possibility (yet to be proven in the experiments) for the chassis to recover to normal position after capsizing (from the bottom up position);
- give a possibility to use section body as an additional turning device for an arm or other device, e.g. a device serving the chassis itself.
- install payload instruments on the soil, without using any dedicated deployment manipulators.

Figure 14. Mongoose-2 section rotation.

A simulation mathematical model was developed for preliminary estimation of mobility of the Mongoose-2
platform. Application of object-oriented simulation allowed for developing a model that uses CAD developments, which led to a rather exact match of dimensional and inertial specifications of the model\textsuperscript{10,11}.

Mathematical simulation of sophisticated technical systems is an important development process already at the design stage. The simulation allows for preliminary estimation of system behavior to a desired degree of precision in the conditions that simulate real physical processes. There are a lot of studies available that describe simulation of mobile wheeled and wheeled walking robots. Besides, subject to application of such study, various models of interaction of the wheels with the soil may be used. Thus and so, an elastic damper connection between the wheel and the bearing surface is assumed for simulation in studies\textsuperscript{12,13}, which allows for considering varying geometry of the terrain. If movement across a plane surface is simulated, it is assumed that the wheels are in fixed contact with the soil\textsuperscript{14}. A more detailed investigation of the interaction between the wheel and the soil means consideration of deformation of the soil, as well as the wheel. Examples of such simulation are presented in \textsuperscript{15,16}.

This study assumes the most convenient, according to the authors, and not less effective method of object-oriented simulation, where the model of contact of the wheel and the bearing surface is described by elastic damper interaction of two polygons\textsuperscript{17}.

A work field with a diagram of simulation model and a fragment of simulation visualization window are presented in Figure 15.

This model consists of the blocks that mathematically describe the solid body model. Each of such blocks is assigned to a certain structural member of the platform. Models of two sections, two pistons and two wheels serve as principal blocks. Each block is connected with other blocks with the help of kinematic interconnections. Pistons can rotate relative to each other, and sections are connected, in their turn, with the pistons by translational and rotational degree of freedom. Wheels blocks are attached, via the rotational degree of freedom, to the sections and pistons, and are also connected, via the mathematical model of contact with the bearing surface. The geometry of the solid bodies was imported from the CAD system.

It was assumed for the development of the Mongoose-2 platform that its passability must exceed that of the Mongoose-1 platform nearly twice. These values should be achieved by some increase in dimensions of the platform and drive power.

One of the most difficult for overcoming type of obstacles, i.e. escarp, was considered in this research, using mathematical simulation. Simulation of overcoming of the escarp was done due to a free articulating link in the middle axis and walking and framework bend drives. The following heights of escarp were considered: for the free articulating link - 500 mm, for overcoming in the walking and framework bend mode - 1,000 mm. Not only determination of the possibility of overcoming such obstacles, but also momenta in drives required for such movement that are necessary for further drive design was the objective of simulation.

A sequence of overcoming the escarp of 500 mm in height with the free articulating link of the middle axle is presented in Figure 16. This sequence represents fragments of visualization of object-oriented simulation.

Figure 15. Work field and simulated Mongoose-2 platform model and simulation visualization window.

Figure 16. Visualization of simulation of overcoming an escarp of 500 mm in height.
Arrows in contact points of wheels in Figure 16 represent qualitative value of normal and tangential reactions to wheels working with the bearing surface. Such representation allows for better understanding of the processes that happen in reference points with the platform moving. Simulation results are presented in Figure 17 as ratios of wheel momenta and simulation time required for overcoming an escarp of 500 mm in height at free articulating link in the middle axis.

Moments of time, when the platform overcomes the escarp with each wheel, are clearly visible in Figure 17. These are represented by peaks in momentum diagrams, and it is especially obvious for the rear wheel, where the largest of all three wheels momentum is required, as long as rear wheels are loaded heavier in movement. According to the results, overcoming of the escarp is rather dynamic in terms of load on the structure by the process, which should be considered for further platform development. Also, discovered momenta are necessary for selecting motors and gear system of wheel drives.

Simulation of overcoming an escarp of 1 m in height was done, based on the experience gained in testing of the Mongoose-1 platform, which allowed for discovering key displacements of sections to overcome such obstacles. Simulation sequence of overcoming the escarp of 1 m in height by the Mongoose-2 platform is given in Figure 18. Similar to the simulation of the escarp of 500 mm in height, arrows indicate force values in contact points of wheels with the bearing surface. According to Figure 18, overcoming of the obstacle was done by means of wheel drives, as well as walking and framework bend drives.

Framework bend drive is the drive that is loaded the most in overcoming of the escarp that is specified in Figure 12 of the sequence. The developed model allowed obtaining the momentum values for simulating escarp overcoming in the framework bend drive. Simulation results are presented in Figure 19. Wheel momenta do not exceed the values obtained as a result of previous simulation, therefore, they are not provided.

As can be seen from Figure 19, the momentum in the framework bend articulating link can be positive, or negative. This is due to the fact that the front section lifts first, when overcoming the escarp, and the rear section lifts next due to the front section somewhat squeezing up against the bearing section. The correct redistribution of the center of mass with the help of walking mechanism drives prevents the platform from overturning, when the sections go up and down. Momentum values for the articulating link of the framework bend drive will be further incorporated in the development of the Mongoose-2 platform for the selection of motor and gear system and for strength calculations.
4. Discussion

According to testing of the Mongoose-1, the designed platform that includes an articulated chassis has enhanced mobility. The height of negotiated obstacles equals to two diameters of the wheel and is limited by the displacement range of the walking mechanism (i.e. the height of an obstacle can be higher). Due to the design of the articulated frame, constant contact of all six wheels with the bearing surface is ensured, when articulated joints are freed, which allows the robotic system to move across rough terrain (ruins of destructed buildings, debris, fallen trees, etc.).

Dimensions of the Mongoose-2 platform are higher than of the Mongoose-1 platform (wheel diameter of the Mongoose-2 is 650 mm vs. 350 mm with the Mongoose-1); therefore, one may assume that the mobility properties of the Mongoose-2 will respectively higher. According to preliminary mathematic simulation of the Mongoose-2 platform, the overcoming of an escarp up to 1 m is possible.

5. Conclusion

At the moment, a six-wheel two-section chassis containing active articulating joints and walking mechanisms ensures the best mobility performance, while demonstrating this advantage being a simple structure, with cost-effectiveness, and the ability to provide high-speed locomotion. At the same time, this design imposes some dimensional and arrangement limitations and on the chassis service equipment and on-board payload:

- when sections fold at 90°, the payload volume must be within the specified limits;
- payload mass must be evenly distributed on both sections;
- the use of three flexible cable loops in articulating joints, which connect the sections and which comprise the electrical power lines with large cross-section wires.

Testing of the Mongoose-2 platform is scheduled to further development phases of this work in order to investigate the off-road capabilities and compare it with the simulation results.

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7. References

