Mechanical Properties of Modern Wheeled Mobile Robots

Submitted: 29th July 2019; accepted: 14th September 2019

Maciej Trojnacki, Przemysław Dąbek

DOI: 10.14313/JAMRIS/3-2019/21

Abstract:
The paper discusses mechanical properties of modern wheeled mobile robots including aspects of kinematics and dynamics. Relevant features of these robots and of used types of wheels are considered. Robots are categorized into six groups according to kinematic structures, which can be obtained using various types of wheels. For each group mechanical properties, which characterize the robots are discussed. Various variants of the robots within particular groups are described and some examples of existing solutions are given. Individual variants of the robots are compared and assessed taking into account the possessed features.

Keywords: *wheeled mobile robot, kinematics, dynamics, kinematic structure, wheel*

1. Introduction

Wheeled mobile robots (WMRs) are often unmanned vehicles, which can be teleoperated or have various levels of autonomy. They can be dedicated to perform dangerous or tedious tasks thus enhancing workers health and safety or releasing people to more creative tasks.

WMRs find more and more practical applications in manufacturing, civil engineering, transportation, agriculture, space exploration, help for disabled and in other sectors of science and technology.

One of the fundamental problems is choice of optimal kinematic structure of a robot for a given application. This problem is associated with selection of appropriate types of wheels, their mutual arrangement, number of used drives etc. The choice of optimal solution is usually a compromise between mechanical properties and complexity, which is directly connected with cost.

In the available literature there are few items that provide guidance for designers and comparison of various solutions of modern robots. One can mention among others works [9] and [10], but they are not comprehensive or are partially outdated.

Therefore, the objective of this paper is comparative analysis of WMRs with various kinematic structures. This analysis takes into account various features of WMRs for which the examples of actual solutions are given. Primarily commercial robots and other selected designs having high Technology Readiness Level are considered. The analysis is limited to solutions of wheeled robots with fixed kinematic structure. The paper does not include reconfigurable and hybrid robots (i.e. robots that combine features of continuous and discrete locomotion). Some examples of hybrid solutions one can find in work [13] and on webpage [32].

2. Features of Wheeled Mobile Robots

Particular solutions of mobile robots are discussed taking into consideration the following features:

- number of control degrees of freedom,
- mobility,
- maneuverability,
- stability of motion,
- dead reckoning,
- complexity of design,
- environment of operation.

Features such as mobility, maneuverability, stability of motion, dead reckoning and complexity of design are described by 3 linguistic levels, that is: bad (or low), medium, and good (or high).

Degrees of Freedom. The important characteristic of mobile robots is their number of Degrees of Freedom (DoFs). Number of DoFs of a mechanical system is the number of independent parameters that define its configuration. There are also known concepts of representational DoFs (related to number of coordinates) and control DoFs (reflecting the number of actuators). The vehicles for which the number of control DoFs is less than representational DoFs are called underactuated, whilst those for which is higher are named overactuated.

Considerations concerning the number of DoFs in WMRs will be limited to the mobile platform only. It means that DoFs related to e.g. manipulators and other non-wheeled effectors are not taken into account. For analyzed examples of robots are given only the numbers of control DoFs. Since motion of WMRs is realized in practice most often in plane, therefore the number of representational DoFs is equal to 3.

Mobility. The term mobility can be defined as robot ability to move with desired parameters of motion in defined conditions of environment, with limitations of the robot itself taken into account [9]. For determination of the mobility, motions of a robot on the ground with various mechanical properties and inclinations are analyzed. Robot ability of negotiation of environment obstacles of various shapes and heights (for example curbs, stairs) is also important. Robot mobility on particular terrain depends on number of factors, including: geometry of locomotion system, center of mass coordinates, properties of wheels (e.g. adhesion, rolling resistance, area of contact with the ground), constraints resulting from characteristics of drives (e.g. power, maximum rotational speed, maximum driving torque), battery parameters (e.g. maximum continuous discharge current) and other [12]. For these reasons, it is difficult to objectively assess the mobility of the robot without realization of simulation and experimental studies.

In this paper the assumption is adopted that the robot possesses good mobility if it meets two of the following requirements:

– is able to overcome obstacles with a height, which is close to the radius of the driven wheels, both in forward and backward directions,
– has the ability of movement in both directions on the ground surface which is inclined at an angle of at least 30 deg and for which are present high values of friction coefficients for wheel-ground pair (e.g. asphalt, concrete, unpaved road).

The robot is characterized by medium mobility, if it meets one of the above mentioned requirements and by bad mobility if none of these conditions is met. Some of the solutions are assessed individually, in which case it is supported by justification.

Maneuverability. The maneuverability is robot ability to change its direction of motion. Maneuverability is especially important in case of movement in narrow spaces, in which the robot should e.g. be able to rotate in place.

The robot is characterized by good maneuverability if it has both the possibility of linear motion in any direction and rotation in place. The robot has medium maneuverability if it meets one of the following requirements:

– is able to rotate in place and perform linear motion in direction which depends on current pose or turning with defined radius,
– is not able to rotate in place and can realize linear motion in any direction independent of the current pose.

Finally, the robot will have bad maneuverability if none of the mentioned requirements is met.

Stability of motion. The stability of motion in case of WMRs is understood as robot resistance to unevenness of the ground during its movement.

The robot has bad stability if as a result of unevenness of the ground it loses contact of one of the driven wheels with the ground and then unintentionally and significantly changes its previous direction of motion. If the impact of the loss of contact by one of the driven wheels causes small change in direction of movement, it is characterized by medium stability, and if this impact is negligible – by good stability.

Dead reckoning. Dead reckoning of a vehicle is the ability of estimation of its location based on estimated speed, direction and time of travel with respect to a previous estimate [2].

In case of WMRs dead reckoning is typically based on odometry of the robot [1]. Therefore, in this study the assessment criterion of dead reckoning will be accuracy of determination of motion parameters of robot mobile platform on the basis of measured angular parameters of spin and turning angle of its wheels.

Complexity of design and cost. The complexity of design of WMRs is first of all related to mechanical and control system design. The important factor is also the number of controlled drives, hence the number of control DoF.

Nowadays, implementation of motion even in case of complex robot kinematic structures does not present major difficulties considering current computing power of controllers, therefore it does not significantly affect the hardware complexity of the solution.

It should be mentioned, that hardware complexity of the design is related to higher cost of manufacturing of the vehicle. The use of a large number of drives requires also the use of highly efficient power supply systems.

Therefore, when assessing the level of complexity of WMRs, first of all the number of drives of locomotion system will be taken into account. Moreover, it will be assumed, that higher complication of design is caused by adding some steering mechanism to a wheel than by adding wheel driving mechanism and that the most complex is the case in which the wheel is both steered and driven. This reasoning is justified in particular in case of small-size robots. Finally, higher complexity of the design causes use of Mecanum wheels or omni-wheels in comparison to standard wheels.

Environment of operation. Type of environment in which the vehicle operates is limited to division into indoor and outdoor environment. The use of indoor can be associated with solutions of at least medium maneuverability, while outdoor with solutions of at least medium mobility and stability of motion. Exceptions to this rule of classification are discussed in case of specific solutions. When it comes to indoor use of a mobile robot the stability of motion is less important than in case of outdoor applications, because indoor environment is typically characterized by smaller unevenness of the ground.

3. Classification of Wheeled Mobile Robots

The considerations concerning classification of WMRs will be started from used types of wheels.

Generally, wheels with the following features are used:

- driven and non-driven,
- steered and non-steered.

By the steered wheel one means such a wheel, which direction can be changed with respect to chassis by control system. In turn, the non-steered wheel is not able to turn (fixed wheels) or it has this capacity, but its turning is not the result of control but is forced by external forces (caster wheels).

Next, depending on the combination of aforementioned features one can distinguish the following types of wheels:
- castor (non-steered and non-driven),
- fixed and non-driven (free wheels),
- fixed and driven,
- steered (steerable) and non-driven,
- steered (steerable) and driven.

In steered wheels the axis of turning generally intersects the axis of spin of wheel, whilst in case of caster wheel these axes are placed in some distance relative to each other. This displacement enables self-turning of wheel under the influence of lateral force acting on it.

In addition, the wheels can be divided into single and twin (dual). This division has generally no influence on the kinematic structure of the robot, but it affects the distribution of stresses between wheels and the ground, and is not taken into account in further considerations.

Special type of fixed and driven wheels represent Mecanum wheels (also named as Swedish) and omni-wheels (or omni-directional wheels). The Mecanum wheels are characterized by the fact that on the circumference they have non-driven rollers, whose axes of rotation are rotated by an angle of 45° in relation to the axis of spin of that wheels (see Fig. 1a). In turn, the omni-wheels have also free rollers, but this time their axes of rotation form 90° angle with respect to the wheel spin axis. Moreover, they are typically dual wheels (see Fig. 1b).

a)

b)

Fig. 1. Example of: Mecanum wheel (a) and double omni-wheel (b) [28]

Wheels have a significant impact on vehicle motion and should be characterized by:
- high adhesion to the surface and resistance to lateral drift,
- adequate load capacity (the ability to carry the load),
- the ability of damping vibrations and shocks,
- low rolling resistance,
- durability (resistance to wear and impact).

As noted in work [3], in the case of lightweight wheeled robots, wheels are usually non-pneumatic. They may have a filling in form of a foam. They geometric parameters and properties are different with respect to those of cars. In case of rovers, wheels are made of metals. Flexibility is obtained by appropriate design of the inner part of the wheel.

What is more, one can notice that in case of WMRs suspension systems are sometimes introduced. Because this type of vehicles do not carry people, vibrations of mobile platform may be acceptable. In some solutions of robots intended for movement in open and unstructured environments the control arms are used to improve mainly robot mobility.

WMRs are typically non-holonomic vehicles, which are subjected to velocities constraints on their motion. In practice, this means that the number of control DoF is less than the number of representational DoF, which is equal to 3.

The exceptions are omnidirectional robots, which are considered holonomic vehicles, since they can realize 3 independent movements: in longitudinal and lateral direction as well as rotation about vertical axis.

Depending on used wheel arrangement and wheel types one can distinguish the following kinematic structures of WMRs:
- differentially driven,
- skid-steered,
- car-like,
- omnidirectional (Mecanum drive, holonomic drive),
- rover-type (robots with high number of driven and steered wheels),
- all wheels steered and driven by only two motors (also called synchro drive).

Particular types of kinematic structures of WMRs are characterized in detail in the next section. The synchro drive structure is not discussed, because nowadays it is rarely used. One of known, older solutions of this type is Nomad 200 robot of Nomadic Technologies, Inc.

4. Mechanical Properties of WMRs

The mechanical properties of various solutions of WMRs are discussed taking into account previously defined features.

4.1. Differentially Driven WMRs

Differentially driven robots typically have 2 fixed and (differentially) driven wheels. They are characterized by simplicity of mechanical design and therefore low cost. They have also medium maneuverability. In order to change direction of motion they can rotate in place. Therefore they are usually applied in closed areas (e.g. rooms). This kind of robots is characterized by bad stability of motion, because they may have tendency to unintended changes of direction of desired movement due to unevenness of the ground and different adhesion of the driven wheels to this ground. For this reason they usually do not have outdoor applications.

Regarding the kinematic and dynamic properties of this type of robots, if they move on an even ground, their motion can be accomplished with negligible slips of wheels. This allows the solution of forward and inverse kinematics problems. Moreover, modeling of dynamics of such systems does not cause much difficulty. In this case, due to good dead reckoning, robot movement can be carried out on the basis of odometry only, so by controlling the wheels [1]. Example of such approach one can find among others in work [4].

One can distinguish solutions of differentially driven robots with 2, 3, 4 or even 6 wheels. The selected solutions of this kind of robots are described below.

Two-wheeled differentially driven robots. Two-wheeled robots can be further divided into those in which the body has to maintain vertical orientation, and those which have horizontal orientation and there is a supporting element e.g. in form of the tail.

The robots, in which the body has to keep vertical posture operate based on a principle of the inverted pendulum. They require additional stabilizer module (control system), similarly like in case of Segways. An example of modern solution of this type is the FLASH robot [6]. Such robots should move on even grounds, which limits their use essentially to the rooms.

Two-wheeled robots with the supporting element have better stability of motion, which makes them suitable for use both indoors and outdoors. Examples of such solutions are the Recon Scout IR robot [30], in which as the supporting element an elastic tail with ball was used. The disadvantage of such solutions is that the tail may introduce additional forces disturbing the movement of robot, which affects the dead reckoning.

Three-wheeled differentially driven robots. In this type of robots 2 fixed (differentially) driven wheels and 1 castor are applied. Kinematic structure of this kind of solution is illustrated in Fig. 2.

With two independently driven wheels can be achieved fairly good maneuverability and negligible slips of wheels in case of movement on even ground. The vehicle can overcome more difficult field obstacles if the movement is carried out in the direction of the driven wheels. Such solutions, however, are the most suitable indoors.

An example of such solution is Pioneer 2-DX robot (Fig. 3) and its successor Pioneer 3-DX [29].

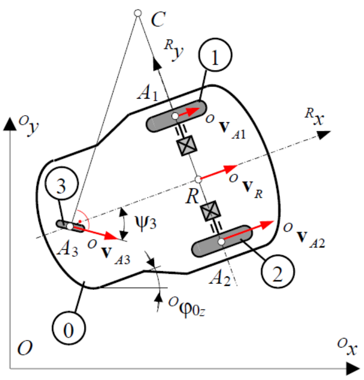

Fig. 2. Kinematic structure of three-wheeled differentially driven robot

Fig. 3. Three-wheeled differentially driven Pioneer 2-DX robot

Four-wheeled and six-wheeled differentially driven robots. In this case, beside 2 fixed (differentially) driven wheels appear also 2 or 4 castors. There are solutions in which 2 castors are in front or rear of the vehicle and the rest of wheels are driven (e.g. TUG [23]) and those in which one castor is in front and one in rear of the vehicle, whilst driven wheels are arranged on sides (e.g. AGVS [25]). The example of six-wheeled solution with 2 castor in front, 2 castors in rear and 2 fixed driven wheels is MiR100 robot [24]. In such solutions an uneven ground can cause robot motion in an unintended direction. Therefore, such robots are designed primarily to move indoors. One of the exceptions is Tango E5 robot [31], which is used outdoors as a lawn mower.

4.2. Skid-steered WMRs

The second discussed in this paper group of robots are the solutions with all wheels fixed. Such robots are called skid-steered due to the fact that, during turning and rotating in place always occurs lateral slip of wheels, that is skid. This is a major drawback of this type of vehicles due to poor energy efficiency and increased wear of wheels (tires) and degradation of the ground. They include typically 4- or 6-wheeled solutions.

They have usually simple and compact design, therefore they are relatively cheap. They are characterized by good mobility and medium maneuverability, i.e. comparable to differentially driven robots. They have also good stability of motion, i.e., robots of this type do not change unintentionally and significantly direction of their motion in the case of uneven ground. For this reason they are often used in open terrain, but also are suitable for closed spaces like rooms, especially in case of four-wheeled solutions.

In skid-steered robots all the wheels are independently driven or wheels on each side of the vehicle are driven by one motor. In the first case, because of use of higher number of drives than representational DoFs, this kind of robots are overactuated. In the second case, the drive on each side of the vehicle is distributed to individual wheels via gears or chains or is transmitted to one wheel and then via toothed belts to the remaining wheels.

Skid-steered robots are complex objects from the point of view of modeling and control. Modeling and control of motion of this type of robots are, among others, the subject of works [7, 11, 15].

Due to slips of wheels occurring during robot turning and rotation in place, in this case one cannot explicitly solve forward and inverse kinematics problems. For the same reason, also more complex is development of dynamics models of such vehicles. Especially complicated is the case when the robot rotates in place on a deformable ground. In such case beside slips of wheels also bulldozing effect appears.

Moreover, due to lateral slips, the wheels are under the influence of lateral forces associated with their contact with the ground. The values of the forces can be high therefore this solution requires the use of strengthened in lateral direction means of mechanical connection of wheels to the mobile platform.

Motion control of this type of robot, due to bad dead reckoning cannot be performed only on the basis of their odometry, that is by controlling the spin of wheel only. In this case it is necessary to measure actual velocities of the robot mobile platform or its pose (posture). For such robots it is advisable to introduce the hierarchical control system, consisting of kinematic (pose) and dynamic controllers. This approach is used, among others, in the works [5, 15]. In turn, in the paper [11] for motion control of the robot the Nonlinear Model Predictive Control (NMPC) method was used.

Four-wheeled skid-steered robots. In these robots all the wheels are driven independently or – more frequently – independently driven are only two wheels, one on each side, and the drive is transmitted to the other wheel on a particular side by toothed belt. The kinematic structure of such solution is illustrated in Fig. 4.

The examples of such robots are Rex [11] and PIAP GRANITE [14] with independent drive on all wheels, as well as PIAP SCOUT and PIAP Fenix [26] (Fig. 5) with 2 driven wheels (one on each side of the robot). Thanks to the use of only 2 drives, one can reduce the size and mass of the robot. This is particularly important if it is necessary to carry a robot by a human.

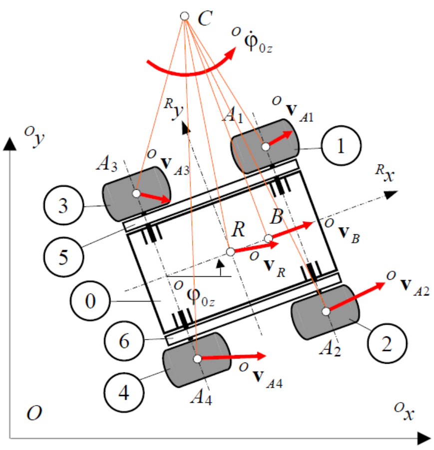

Fig. 4. Kinematic structure of four-wheeled skid-steered robot

Fig. 5. Four-wheeled skid-steered PIAP Fenix robot [25]

Six-wheeled skid-steered robots. In case of such robots the most typical is independent drive on all wheels (as for IBIS robot [PIAP] shown in Fig. 6) or one motor is used for each side of the robot and drive is then transmitted to the wheels via gears or chains. In an independent drive typically each wheel on a given side of the robot is controlled with control signal of the same value. Drawback of this solution is that the angular velocities of spin of the individual wheels differentiate depending on the conditions of interaction of the wheels with the ground.

Fig. 6. Six-wheeled skid-steered IBIS robot [26]

The application of higher number of wheels decreases the values of forces exerted on the ground by a single wheel and increases robot mobility among others on a deformable terrain.

In six-wheeled solutions the control arm systems are often introduced, to guarantee continuous contact of all wheels with the ground. In the control arm systems of WMRs usually shock absorbers are not applied, because, as noticed in work [9], they are justified in case of motion of the vehicles with velocities higher than 8 m/s.

If control arms are not used, one can place axles of center wheels a little lower, which reduces the resistance of outer wheels (i.e. wheels located at the corners of a mobile platform) during robot turning, thus decreasing also lateral and longitudinal slips of wheels.

4.3. Car-like WMRs

The next group of wheeled mobile robots includes vehicles whose kinematic structure is similar to a car. The main characteristic features of car-like robots are typically limited steering range of steered wheels. The consequence of such solution is the inability of rotation of the robot in place. Due to this fact such solutions are used mostly outdoors. Similarly to cars, in mobile robots the differential mechanism is sometimes used for drive of the wheels.

The most common robotic vehicles belonging to this group have exactly the same kinematic structure as a car, that is, they are equipped with four wheels, two of which are steered, and they can be driven by two front wheels, by two rear wheels or by all wheels. In such solutions for steering the wheels usually Ackerman mechanism is used, whilst for driving the wheels often differential mechanism is applied. Instead of Ackerman mechanism one can use two motors to independently set the steering angles of the steered wheels. This kind solution presented in Fig. 7 can be mechanically simpler then Ackerman mechanism and is especially preferred in case of small-size robots.

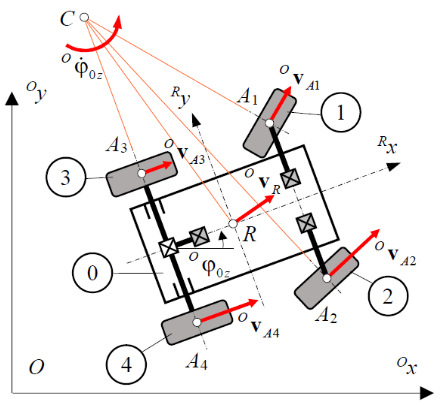

Fig. 7. Kinematic structure of four-wheeled car-like robot

Car-like robots are solutions of medium complexity, but by virtue of using known and proven automotive solutions, design of this type of robots does not cause major difficulties. Furthermore, when using two drives – one for driving and the other one for steering the wheels, such solution may also be relatively cheap.

Such solutions of robots are used primarily in agriculture, examples of which can be found in [16]. This is not accidental, because if one compares mechanical properties of four-wheeled car-like robots with other solutions one can notice that this solution is optimal for such applications. Depending on the number of driven wheels the car-like robots are characterized by medium or good mobility, good stability of motion and good dead reckoning. In such applications the differentially driven solutions are inefficient because of too low stability when moving on uneven terrain and the possibility of sinkage of castor wheels in soft ground. The skid-steered robots cause devastation of soil and may bury themselves during cornering. The omnidirectional robots are not suitable due to the loss of characteristics of Mechanum or omni-wheels in case of contamination by soil. Finally, the rover-type robots are too complex and therefore too expensive.

The example of such solution is Vine robot [17] shown in Fig. 8 dedicated for application in vineyards. Another example is represented by Trakür robot [19], designed to apply pesticides in greenhouses.

Fig. 8. Car-like Vine robot [17]

This group of robots includes also three-wheeled solutions, which are however rarely used. The worst mobility have three-wheeled mobile robots with one driven wheel, which have difficulty in overcoming even small obstacles.

4.4. Omnidirectional WMRs

Another group of wheeled mobile robots are omnidirectional robots also called holonomic robots, because they have zero nonholonomic constraints imposed on vehicle velocities. This means that the robot can move independently in longitudinal and lateral directions and rotate around a vertical axis at the same time. This is achieved by using Mecanum wheels or omni-wheels, which were described earlier.

Omnidirectional robot wheels are relatively mechanically complex as compared to designs of other wheels which at the same time makes them relatively expensive. Moreover, in this type of robots all the wheels are independently driven and controlled, which requires at least three motors. In case of omnidirectional robots a little more complicated is also solution of kinematics problems and consequently the control of motion of the mobile platform.

The omnidirectional robots are characterized by very good maneuverability – they can simultaneously rotate in place and move in any direction. They do not have good stability of motion because they motion depends critically on velocity of each wheel. If one of them loses contact with the ground then the robot moves in nonintentional direction. Therefore, they should move on even terrain. Moreover, they have inferior dead reckoning to differentially driven, car-like, rover-type and synchro drive robots but superior to skid-steered ones. Therefore, in order to ensure high accuracy of movement, the robot motion control should not be based on its odometry only.

Such solutions are very good choice in indoor applications but cannot be used outdoors due to the loss of wheel omnidirectional characteristics in case of roller contamination, for example by sand, mud or snow.

The kinematic structure of the robot with omni-wheels is named the holonomic drive, whilst with Mecanum wheels the Mecanum drive.

Holonomic drive. In the case of use of so-called holonomic drive, the wheels are arranged in such a way that their axes of rotation intersect at a single point. Robots with holonomic drive usually have three and less often four wheels. Kinematic structure of holonomic robot with three wheels is illustrated in Fig. 9.

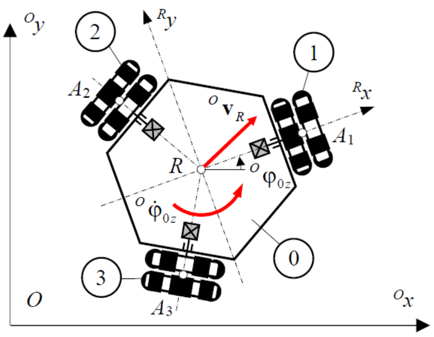

Fig. 9. Kinematic structure of three-wheeled robot with holonomic drive

The examples of such solutions of NEXUS robot company [28] are kits 10003 (three-wheeled drive) shown in Fig. 10 and 10008 (four-wheeled drive).

Fig. 10. Three-wheeled robot with holonomic drive by Nexus robot [28]

Mecanum drive. This type of robots are usually four-wheeled solutions with Mecanum wheels. In this case wheel arrangement can be the same as for skid-steered robots, that is, rotation axes of wheels are parallel to each other. Kinematic structure of this kind is shown in Fig. 11.

Both four-wheeled holonomic and Mecanum drives result in vehicles being overactuated because they use four drives in locomotion system.

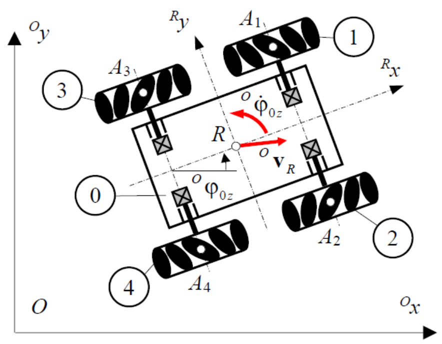

Fig. 11. Kinematic structure of four-wheeled robot with Mecanum drive

The examples of omnidirectional robots with Mecanum drive are kit 10011 of Nexus robot company [28] and MPO-500 robot of Neobotix GmbH company [27] shown in Fig. 12. MPO-500 robot is dedicated for autonomous transport systems in industrial environments.

Fig. 12. MPO-500 robot with Mecanum drive by Neobotix GmbH [27]

4.5. Rover-type WMRs

The last discussed in this paper group of WMRs covers rover-type robots. Not only solutions of rovers will be discussed but also vehicles that have similar kinematic structures.

The rover-type WMRs have high number of motors for driving and steering the wheels, therefore they are classified as highly overactuated vehicles. For this reason they are usually the most complex, hence expensive WMRs. However, they are solutions with very good kinematic and dynamic properties. They are characterized by the best mobility among all types of WMRs. Thanks to the possibility of independent steering of multiple wheels they can rotate in place and also in some solutions, that is with all steered wheels, they can move in any direction. This kind of the vehicles have therefore good maneuverability. What is more, they can move with small slips of wheels, hence they are characterized by good dead reckoning. For safety reasons and in order to reduce slip and sinkage of wheels on soft grounds they usually move at low velocity.

The example kinematic structure of four-wheeled rover-type robot is shown in Fig. 13.

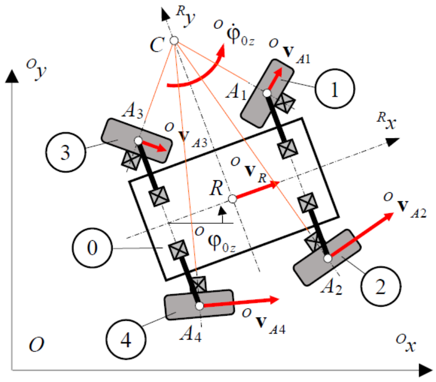

Fig. 13. Kinematic structure of four-wheeled rover-type robot

The rovers are usually six-wheeled solutions with independently driven and steered all wheels or with independently driven all wheels and steered only outer wheels. For driving the wheels often direct-drive motors are used, i.e., they are placed in the wheel hubs. This is due to the use of control arm systems and the fact that often their wheels are both driven and steered.

The examples of such vehicles are Curiosity [21] shown in Fig. 14 and ExoMars rover [22].

It should be noted that the rovers are also developed for various student competitions. In this case, primarily because of a limited budget, simple solutions are predominant, usually containing six independently driven and non-steered wheels. For this reason, the kinematic structures of such solutions are typical for previously discussed skid-steered robots, so they have typical for them mechanical properties. One of many examples of such vehicles are rovers designed by students of the Bialystok University of Technology, Poland [20].

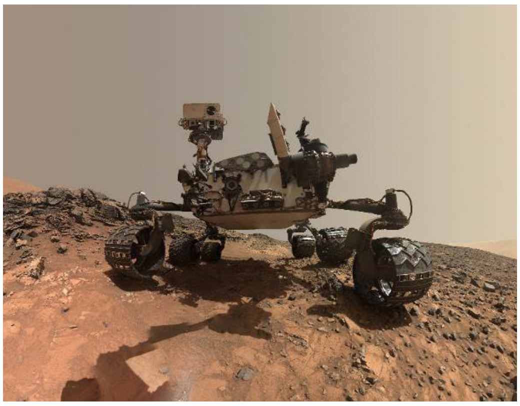

Fig. 14. Six-wheeled Curiosity rover [20]

The rovers are dedicated for outdoor applications, but due to their characteristics such as good maneuverability and dead reckoning, in case of relatively small designs they could be also used indoors.

It is also possible to find rover-type robots with four wheels. The example of them is AZIMUT research robot [8] shown in Fig. 15, dedicated for indoor applications. The other examples include vehicles of American Robot Company (AMBOT) [18], such as GRP 4400 (four-wheel independent drive, four-wheel steering) and GRP 2400 (two-wheel independent drive, four-wheel steering), which are dedicated for outdoor applications. In turn, the example of modern rover with four wheels is Interact Centaur [18], which is a customized version of the remote controlled platform manufactured by AMBOT.

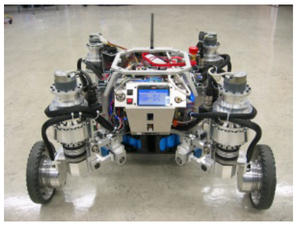

Fig. 15. Four-wheeled rover-type AZIMUT robot [8]

5. Conclusion

The discussed in the previous sections various types of WMRs are compared taking into account selected features associated with their mechanical properties. The result of this comparison is given in Table 1. Five types of kinematic structures were taken into considerations, for which are specified the variants of drive, steering and the number of wheels. Examples of robots are given for each variant.

The selected features used for comparison of individual solutions include: number of control DoFs, environment of operation, mobility, maneuverability, stability of motion, dead reckoning and complexity (directly associated with cost of particular solution).

The conducted assessment of particular types of WMRs is qualitative but justified by previous discussion based on the professional experience of authors and supported by available literature.

After analysis of information presented in Table 1, one can notice among others that:

- differentially driven robots are generally low-cost solutions dedicated for indoor applications, having medium performance in this kind of environment;
- skid-steered robots can operate both indoor and outdoor having at least medium performance but their main disadvantage is large slip of wheels, hence they have bad dead reckoning and tend to degrade the ground;
- car-like robots understood as unmanned vehicles are dedicated for outdoor applications, especially in agriculture, however due to bad maneuverability they are rarely used in robotics;
- omnidirectional robots are used in indoor applications and in this environment they have the best maneuverability;
- the rover-type solutions have the best performance of locomotion system but their disadvantages are high complexity of design and cost.

To sum up, it can be concluded that taking into account all the analyzed features of WMRs there is no single ideal solution in all aspects. Selection of a kine-

Tab. 1. Comparison of modern WMRs according to selected features

Type of kinematic structure	Variant of drive	No. of wheels	Examples	Selected features						
				No. of control DoF	Environment of operation	Mobility	Maneuverability	Stability of motion	Dead reckoning	Complexity of design
Differentially driven	2 fixed, driven wheels in rear and 2 castors in front	4	Tango E5 Series II [31]	2	Outdoor	Medium	Medium	Medium	Good	Low
	2 fixed, driven wheels in center and 2 castors	4	TUG [23], AGVS [25]	2	Indoor	Bad	Medium	Bad	Good	Low
	2 fixed, driven wheels in center and 4 castors	6	MiR100 [24]	2	Indoor	Bad	Medium	Bad	Good	Low
	2 fixed, driven wheels and 1 castor	3	Pioneer 3-DX [29]	2	Indoor	Bad	Medium	Bad	Good	Low
	2 fixed, driven wheels and vertical body	2	FLASH [6]	2	Indoor	Bad	Medium	Bad	Good	Medium
	2 fixed, driven wheels and tail	2	Recon Scout IR [30]	2	Indoor & outdoor	Medium	Medium	Bad	Medium	Low
Skid-steered	All fixed & driven wheels	6	IBIS [26]	2 (6)	Indoor & outdoor	Good	Medium	Good	Bad	Low (Medium)
		4	PIAP Fenix [26], Rex [11]	2 (4)	Indoor & outdoor	Good	Medium	Good	Bad	Low (Medium)
Car-like	2 steered & 2 (or 4) driven wheels	4	Vine [17], Trakür [19]	2 (3)	Outdoor	Medium (Good)	Bad	Good	Good	Medium
Omnidirectional	Mecanum drive	4	MPO-500 [27], 4WD (10011) [28]	4	Indoor	Medium	Good	Bad	Medium	Medium
	Holonomic drive	4	4WD (No. 10008) [28]	4	Indoor	Medium	Good	Bad	Medium	Medium
	Holonomic drive	3	3WD (No. 10003) [28]	3	Indoor	Medium	Good	Bad	Medium	Medium
Rover-type	All driven wheels, 4 (outer) of which steered	6	Curiosity [21]	10	Outdoor (indoor)	Good	Medium	Good	Good	High
	All wheels steered and driven	6	ExoMars [22]	12	Outdoor (indoor)	Good	Good	Good	Good	High
	All wheels steered and 2 of which driven	4	GRP 2400 [18]	6	Indoor & outdoor	Good	Medium	Good	Good	Medium
	All wheels steered and driven	4	Interact Centaur and GRP 4400 [18], Azimut [8]	8	Indoor & outdoor	Good	Good	Good	Good	High

matic structure should be based on intended application of a robot and its planned market price. The authors hope that this study will be useful for designers of WMRs and help them to make an informed choice of solution for a given application of a robot.

AUTHORS

Maciej Trojnacki* – ŁUKASIEWICZ Research Network – Industrial Research Institute for Automation and Measurements PIAP, Warsaw, 02-486, POLAND, mtrojnacki@piap.pl.

Przemysław Dąbek – ŁUKASIEWICZ Research Network – Industrial Research Institute for Automation and Measurements PIAP, Warsaw, 02-486, POLAND, pdabek@piap.pl.

*Corresponding author

REFERENCES

[1] J. Borenstein, H. R. Everett, and L. Feng. “”Where am I?” Sensors and Methods for Mobile Robot Positioning”. Technical report, The University of Michigan, 1996.

[2] P. Corke, *Robotics, Vision and Control: Fundamental Algorithms In MATLAB®*, Springer Tracts in Advanced Robotics, Springer International Publishing, 2017.

[3] P. Dąbek and M. Trojnacki, “Requirements for Tire Models of the Lightweight Wheeled Mobile Robots”. In: J. Awrejcewicz, K. J. Kaliński, R. Szewczyk, and M. Kaliczyńska, eds., *Mechatronics: Ideas, Challenges, Solutions and Applications*, 2016, 33–51
DOI: 10.1007/978-3-319-26886-6_3.

[4] Z. Hendzel, “An adaptive critic neural network for motion control of a wheeled mobile robot”, *Nonlinear Dynamics*, vol. 50, no. 4, 2007, 849–
–855
DOI: 10.1007/s11071-007-9234-1.

[5] Z. Hendzel and M. Trojnacki, “Neural Network Control of a Four-Wheeled Mobile Robot Subject to Wheel Slip”. In: J. Awrejcewicz, R. Szewczyk, M. Trojnacki, and M. Kaliczyńska, eds., *Mechatronics – Ideas for Industrial Application*, 2015, 187–201
DOI: 10.1007/978-3-319-10990-9_19.

[6] J. Kędzierski and M. Janiak, “Budowa robota społecznego FLASH (Construction of FLASH social robot)”. In: K. Tchon and C. Zielinski, eds., *Prace Naukowe Politechniki Warszawskiej. Elektronika*, vol. 182, 2012, 681–694 (In Polish).

[7] K. Kozlowski and D. Pazderski, “Practical Stabilization of a Skid-steering Mobile Robot – A Kinematic-based Approach”. In: *2006 IEEE International Conference on Mechatronics*, 2006, 519–524
DOI: 10.1109/ICMECH.2006.252581.

[8] M. Lauria, F. Michaud, M. Legault, D. Letourneau, P. Retornaz, I. Nadeau, P. Lepage, Y. Morin, F. Gagnon, P. Giguere, J. Fremy, and L. Clavien, “Elastic locomotion of a four steered mobile robot”. In: *2008 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2008, 2721–2722
DOI: 10.1109/IROS.2008.4650759.

[9] P. Sandin, *Robot Mechanisms and Mechanical Devices Illustrated*, McGraw-Hill/TAB Electronics: New York, 2003.

[10] R. Siegwart, I. R. Nourbakhsh, and D. Scaramuzza, *Introduction to autonomous mobile robots*, MIT Press: Cambridge, 2011.

[11] K. Tchoń, K. Zadarnowska, Ł. Juszkiewicz, and K. Arent, “Modeling and control of a skid-steering mobile platform with coupled side wheels”, *Bulletin of the Polish Academy of Sciences. Technical Sciences*, vol. 63, no. 3, 2015
DOI: 10.1515/bpasts-2015-0092.

[12] M. Trojnacki, “Analysis of influence of drive system configurations of a four wheeled robot on its mobility”, *Journal of Automation, Mobile Robotics and Intelligent Systems*, vol. 6, no. 4, 2012, 65–70.

[13] M. Trojnacki, “Modelling the motion of the mobile hybrid robot”, *International Journal of Applied Mechanics and Engineering*, vol. 15, no. 3, 2010, 885–893.

[14] M. Trojnacki and P. Dąbek, “Studies of dynamics of a lightweight wheeled mobile robot during longitudinal motion on soft ground”, *Mechanics Research Communications*, vol. 82, 2017, 36–42
DOI: 10.1016/j.mechrescom.2016.11.001.

[15] M. Trojnacki, P. Dąbek, J. Kacprzyk, and Z. Hendzel, “Comparative Analysis of Posture Controllers for Tracking Control of a Four-Wheeled Skid-Steered Mobile Robot – Part 1. Theoretical Considerations”. In: R. Jabłoński and T. Brezina, eds., *Advanced Mechatronics Solutions*, 2016, 583–604
DOI: 10.1007/978-3-319-23923-1_85.

[16] “Robots in agriculture”. c2015, Into Robotics, www.intorobotics.com/35-robots-in-agriculture/. Updated on: 2018-01-14, accessed on: 2019-10-02.

[17] “A robot to help improve agriculture and wine production”. c2015, ScienceDaily, www.sciencedaily.com/releases/2015/01/150128113713.htm. Accessed on: 2019-10-02.

[18] "American Robot Company Homepage", c2015, American Robot Company, www.ambot.com. Accessed on: 2019-10-02.

[19] "Argentine greenhouse robot brings automation to the masses". c2012, CBS Interactive, www.zdnet.com/article/argentine-greenhouse-robot-brings-automation-to-the-masses/. Accessed on: 2019-10-02.

[20] "The argo project". Bialystok University of Technology, http://argo.pb.edu.pl/en/. Accessed on: 2019-10-02.

[21] "Home | Curiosity – NASA's Mars Exploration Program". National Aeronautics and Space Administration, https://mars.nasa.gov/msl/. Accessed on: 2019-10-02.

[22] "ESA – Robotic Exploration of Mars". c2000-2019, European Space Agency, https://exploration.esa.int/web/mars/. Accessed on: 2019-10-02.

[23] "Mobile robots for healthcare – Pharmacy, Laboratory, Nutrition and EVS". c2018, Aethon, https://aethon.com/mobile-robots-for-healthcare/. Accessed on: 2019-10-02.

[24] "Frontpage | Mobile Industrial Robots". c2019-2020, Mobile Industrial Robots A/S, www.mobile--industrial-robots.com. Accessed on: 2019-10-02.

[25] "AGVS | Robotnik". Robotnik Automation S.L.L., www.robotnik.eu/mobile-robots/agvs/. Accessed on: 2019-10-02.

[26] "Counter terrorism robots – special vehicles, equipment and tools by PIAP". c2015, ŁUKASIEWICZ – Instytut PIAP, www.antiterrorism.eu. Accessed on: 2019-10-02.

[27] "Neobotix: Homepage". Neobotix GmbH, www.neobotix-robots.com. Accessed on: 2019-10-02.

[28] "NEXUS Robot". c2012, Nexus Automation Limited, www.nexusrobot.com. Accessed on: 2019-10-02.

[29] "Pioneer 3-DX". Generation Robots, www.generationrobots.com/ media/Pioneer3DX-P3DX--RevA.pdf. Accessed on: 2019-10-02.

[30] "Recon Scout IR". c2018, ReconRobotics, Inc., https://reconrobotics.com. Accessed on: 2019-10-02.

[31] "Tango E5 Series II | Robotic Mower | John Deere UK & IE". c2019, Deere & Company, www.deere.co.uk/en/mowers/robotic-mower/tango-e5--series-ii/. Accessed on: 2019-10-02.

[32] "Special Off-road Vehicles". Jean-Marc Maclou, www.unusuallocomotion.com. Accessed on: 2019-10-02.