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# DESIGN DEVELOPMENTS OF VIBRATION-DRIVEN MOBILE ROBOTS

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***Abstract:*** *In this paper three new design ideas and the corresponding prototypes built recently are reported and discussed. The prototype robots are capable of achieving forward and backward motion by still using one-way bearings. In these designs the one-way bearings are installed out of the wheel's hubs and are activated either electro-magnetically or electro-mechanically to accomplish forward or backward motion. For comparison reasons, regarding the robot's performance, all prototypes employ the same propulsion mechanism as that in the first and the second designs discussed in articles (Loukanov, I.A. 2014b) and (Loukanov, I.A. 2015) respectively.*

***Keywords:*** *Resonance vibrations, Inertia propulsion, One-way bearing, Spring system, Linear damping.*

## INTRODUCTION

Vibration-driven robots are new contemporary trends in the robot propulsion in recent years. They are moving due to the of inertia forces generated by two synchronized counter-rotating unbalanced masses (Tolchin 1977, Loukanov 2014(a), Loukanov 2014(b)). Some of the robots described in this article are using one-way bearings installed in the wheel hubs, as predicted long time ago by (Goncharevich 1986), while others use one-way bearings placed outside of the wheel's hubs. Many other drives using internally oscillating masses are subjected to intensive studies (Chernousko et al. 2002, 2005; Jatsun et al. 2001. 2007, 2009) including numerous patents granted (Dean 1959, Cherepanov 1996, Hoshino 2005, Robertson 2009). The major benefits of the wheeled robots using one-way rotating bearings are that they don't require complex power transmissions such as gear trains, prop shafts, differential mechanism, final drives etc. They achieve motion on surfaces of different nature without applying driving torques to the wheels. This prevents slipping of the wheels during motion but they still require minimal friction support from the contacting surface. Therefore the vibration drives are not contradicting the Newton laws of motion and hence are not reactionless drives. In this regard, the principle of conservation of energy and momentum are valid (Provaditis 2011, 2014; Provadities & Camble 2014 etc,). According to the experience of authors the major disadvantage of unidirectionally moving robots is the lack of ability to reverse (Loukanov & Stoyanov 2015; Loukanov et al. 2016(a) and 2016(b)).

In this paper three new design ideas and the corresponding prototypes built in the recent years are reported and discussed. They are capable of achieving forward and backward motion by still using one-way bearings. In these designs the one-way bearings are installed out of the wheel hubs and are activated either electro-magnetically or electro-mechanically to accomplish forward or backward motion. For comparison reasons, regarding the robot's performance, all prototypes employ the same propulsion mechanism as that in the first and the second designs discussed in the articles (Loukanov et al. 2016(a), 2016(b)) respectively.

## 1. Materials and Methods

In this paper three new designs are presented and discussed regarding their abilities to achieve both forward and backward motions as compared to the first and second unidirectionally moving robots shown in Fig. 1 and Fig. 2 respectively. The major parts involved in their designs are indicated by the corresponding part numbers while the directions of motion are designated by blue arrows. The red arrows show the direction of oscillations of the propulsion mechanism denoted by a single-degree of freedom oscillating system. The first two robots use one-way rotating bearings installed in the hubs of the wheels as outlined in articles (Loukanov & Stoyanov 2015; Loukanov et al. 2016(a)). The one-way rotating bearings allow a unidirectional motion only in forward direction.

Fig. 1 and Fig 2 illustrate the first and the second robot prototypes respectively moving in one direction only. The first design (Fig.1) was an attempt to prove the concept of the vibration propulsion method and ready mechanical elements are used in this design. In fact this design suffered of unsatisfactory performance. During tests it was found that although a forward motion was achieved during resonance of the propulsion mechanism (shaker) it was accompanied with large turning moments about the wheel axes. The latter generated a galloping motion of the robot accompanied with separation and jumping off the ground by the front or rear wheels. The analysis revealed that the reason for this problem is the high position of the mass centre of the propulsion mechanism with respect to the wheel axes. Thus the inertia forces forced the robot to gallop due to the created turning moments about the wheel axes. To correct the situation a new design was proposed, shown in Fig. 2, build and successfully tested.

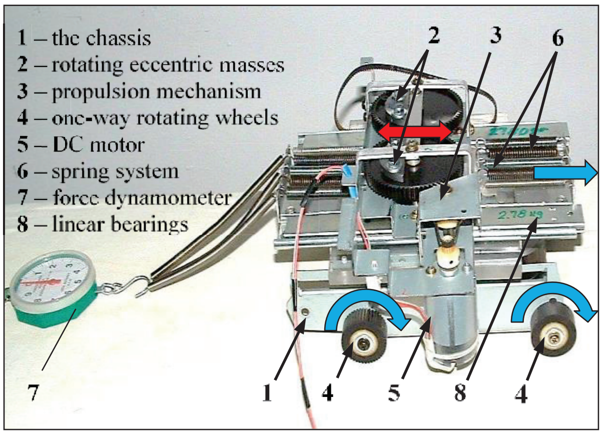


**Fig. 1.** First conceptual prototype of vibration-driven robot, known in the literature as Vibrobot, designed, build and first tested, Aug. 2011

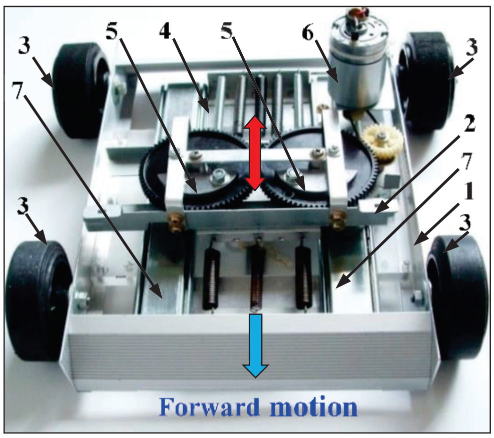


**Fig. 2.** Second prototype: 1- chassis; 2- shaker; 3- wheels with one-way bearings; 4- springs; 5- unbalanced masses; 6 - DC motor; 7- linear bearings, Feb. 2012

Since the resonance conditions are important in achieving high forward velocity it was decided to place the mass centre of the propulsion mechanism (shaker) as low as possible. The propulsion mechanism is redesigned and renovated by placing the mass centre considerably low. These changes were achieved by moving the DC motor from the outside of the robot chassis to the inside of the oscillating system as well as placing the mass centre of the shaker close to the level of the wheel axis.

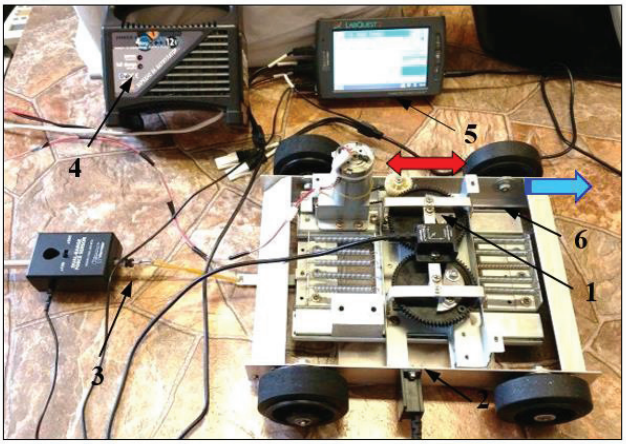


**Fig. 3.** Experimental setup of second prototype of the vibration-driven robot, 2014-2015, where: 1 and 2 - accelerometers; 3- load sell; 4- power source and motor speed controller; 5- LabQuest data measuring and logging system, 6- linear bearings, (2014-2015)

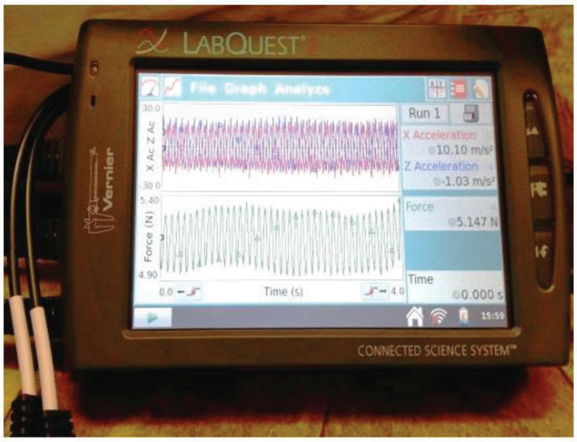


**Fig. 4.** Close view of the measuring and data logging electronic system LabQuest, measuring and recording the accelerations of the shaker and the chassis as well as the towing force created by the robot as tested on a polyvinyl leveled surface

The second design shown in Fig. 2 was presented in numerous scientific seminars and conferences. It was studied theoretically and experimentally by measuring the parameters of the system as shown in Fig. 3 and Fig. 4. The results are reported in the articles (Loukanov & Stoyanov 2015 and Loukanov et al. 2016a). The robot is investigated with the objective to identify more precisely the parameters of the oscillating system by using the experimental data obtained by (Loukanov & Stoyanov 2015). The Dynamics of the second robot is considered in articles (Loukanov et al. 2016(a) and 2016(b)), and the effects of the system's parameters on the mean velocity and dynamic intensity of the robot have been analysed. It is verified that increasing the mean velocity requires a suitable combination of the most influencing parameters such as spring stiffness, resonance frequency and the damping in the oscillating system.

Figs. 3 and 4 illustrate the experimental setup used in studying the one-way moving robot, where accelerations and towing forces are measured and analysed. For this reason the robot is equipped with a 2D accelerometer-1 fitted to the propulsion mechanism and one-dimensional accelerometer fixed to the chassis-2 (Fig. 3). The accelerations are measured by the accelerometers and the towing force by a load cell of 10 N capacities. Data are saved and processed by means of the LabQuest-data-logging system, as shown in Fig. 4, and the results for the logarithmic decrements, towing force and acceleration amplitudes as well as the resonance frequencies are obtained. The results are analysed and reported in articles (Loukanov & Stoyanov 2015 and Loukanov et al. 2016a).

Figs. 5, 6 and 7 illustrate the principle of propulsion of the unidirectionally moving robots, the design of a one-way rotating bearing and the positive propulsion impulses of the inertial force. This principle is modified and used in the propulsion of the reversible robots. Simply the one-way bearings cut the undesired branches of the impulse of the inertia forces and the remaining impulses are applied to the chassis of the robot to accomplish the preferred direction of motion. Fig. 5 shows the sinusoidal shape of the impulse of the inertia force, while Fig. 7 demonstrates the remaining

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shape of the same impulse after the action of the one-way bearings. In this case the robot will attain a forward motion. Inversely for a backward motion Fig. 7 will appear placed upside down, where the negative impulses will be directed downwards and as a result the negative impulses will produce a backward motion.

At the final stage of the analysis a dynamic syntheses is carried out to optimize the robot parameters and the optimum values obtained to be used in order to improve the robot performance (Vitliemov et al. 2016).

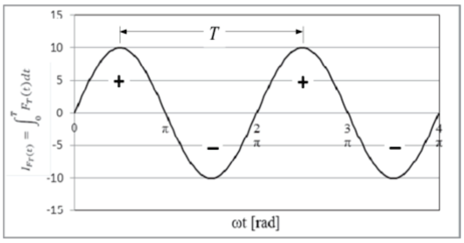


**Fig. 5.** The impulse of the inertial force generated by the robot vibration propulsion mechanism

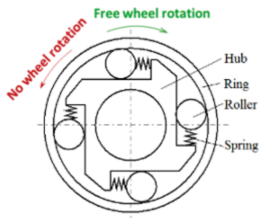


**Fig. 6.** The internal design of a one-way rotating bearing

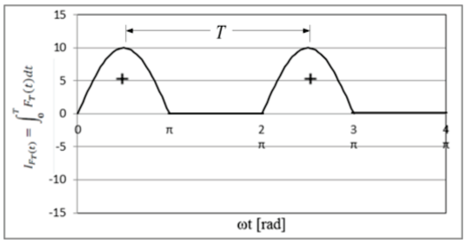


**Fig. 7.** The effect of one-way bearings upon the shape of the force impulse by cutting the negative branches of impulses

Although a lot of developments took place in improving the one-way robot's forward velocity achieving 200-300 mm/s and a towing force 8.5 N, the major weakness still remains, they are not capable of reversed motion. In terms of their practical applications this fact is an essential disadvantage and a barrier for more applications.

In this regard it is decided that the robot design to be modified in order to increase their manoeuvrability by achieving reversed motion by still using one-way rotating bearings. The former design is altered by taking the one-way bearings out of the wheels hubs and placed between the wheels. They are attached to two symmetrically located carriers positioned on each side of the chassis. The carriers are linear bearings having one of the races fixed to the chassis and the other ones carrying two friction rollers, each of them equipped with one-way rotating bearing.

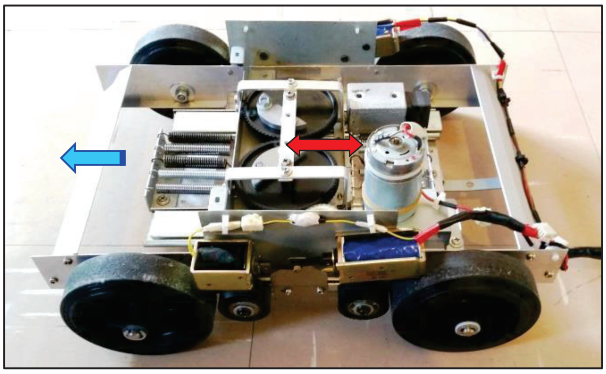

**Fig. 6.** Third prototype of vibration driven robot equipped with an electro-magnetically activated reversing mechanism to achieve forward and backward motion, triggered by an electric switch, completed Sept. 2015

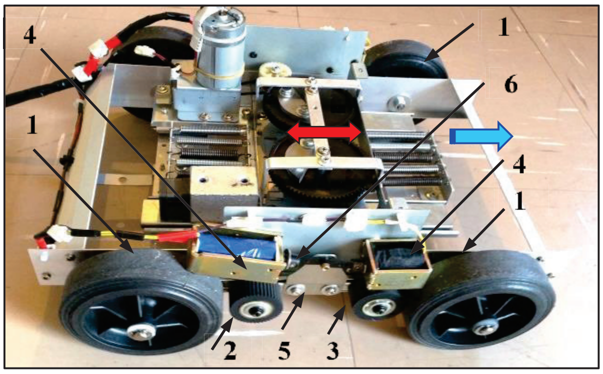


**Fig. 7.** The opposite side of the reversing mechanism, where: 1- free wheels, 2- friction roller for forward motion, 3 - friction roller for rearward motion, 4 - electromagnets, 5 - roller carrier mounted on linear bearings, 6 - connecting rods

Fig. 6 and Fig. 7 illustrate the electro-magnetically actuated reversing mechanism, the location of carrier 5 as well as the friction rollers 2 and 3. Each roller has one-way rotating bearing installed in such a way that they could rotate only opposite to each another; one permits forward motion - 2 and the other allows a backward motion - 3 of the robot. The two sets of carriers are fixed to the chassis on each side of the robot and located between the free rotating wheels. The friction rollers are activated to move either in the forward or in rearward direction by means of a pair of two separate electromagnets; one pair is powered for a forward and the other one for a rearward motion. These are seen in Fig. 6 and shown closely in Fig. 7. Each pair of rollers are mounted in a way to get into friction contact with the outer surface of the free rotating wheels and produce forward or backward motion of the robot respectively. This is achieved by means of electromagnets pushing friction rollers to come into friction contact either with the two front wheels or with the rear ones in pairs. The core of each pair of electromagnets - 4 is connected to each of the carriers - 5 by individual connecting rods - 6 as shown in Fig. 7. The desired direction of motion of the robot is achieved by shifting the carriers either in forward or rearward direction. This is arranged by electrifying either the front electromagnets or the rear ones separately, but in pairs for each group of two wheels. For example, the friction rollers - 2 are to be coupled frictionally to the front wheels of the robot to produce a forward motion and the friction rollers -3 to join frictionally with the rear wheels to obtain backward motion of the robot.

There are two separate power supply units used to power and control the robot: one delivers 24-48 Volts for actuating the electromagnets and the other supplies an adjustable voltage from 0 to 14.4 Volts designed for varying the speed of the DC motor of the propulsion mechanism to set it in resonance. The power supply units are shown in Fig. 8 along with the direction of motion of the control switch.

Articles (Bolotnik 2011, Vitliemov 2016) specified that the resonance is the most important condition to set and achieve a maximum forward velocity of the robot as well as generating a maximum propulsion force. The latter is important in overcoming surface obstacles, which may occur over different soil and ground conditions.

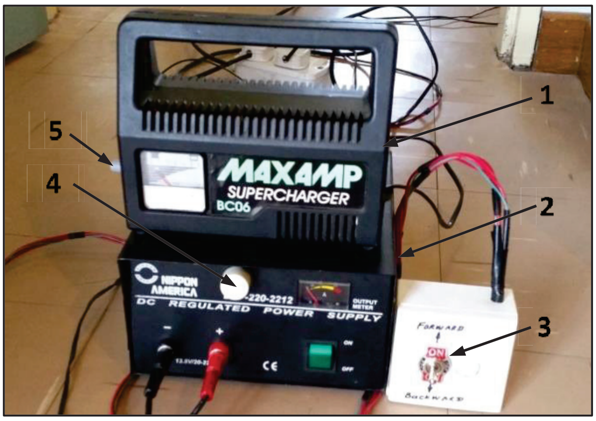


**Fig. 8.** The DC power supply units used to power and control the robot:
**1** – supplies (0-14.4 V), **2** – (24-48 V), **3** – the control switch for forward-backward motion; **4**, **5** – are the knobs of voltage controls

When tested the robot shows good performance and reasonable forward and backward motion. It is very easy to change the direction of motion simply by switching the positions of the friction rollers in pairs. In this design only two out of the four wheels provide friction contacts with the ground during forward or backward motion.

Despite the good general performance of the electro-magnetically controlled reversing mechanism the robot design suffers of some genuine weaknesses. These are:

- The clamping force between friction rollers and the outer surface of the wheels is not enough due to insufficient electromagnetic force leading to a slow motion of the robot.
- Since the electromagnets are installed almost collinear to the lon.
- Gitudinal vibrations of the chassis this provokes reduction of the clamping force because of the splitting effects of vibrations.

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- The use of two different power supply units is a technical and practical problem as they have to be controlled separately during operation of the robot, making the robot control difficult for the operator.
- A continuous power supply to the electromagnets is required to maintain the clamping force between friction rollers and the wheels, thus ample cooling is necessary to dissipate the generated heat in the electromagnets.
- Due to the rigid assembly of the wheel's axes to the chassis the wheels are unable to copy the terrain and hence maintaining a poor contact with the ground. As a result from time to time only 3 out of four wheels are contacting the ground and among them only one may support propulsion. This situation results in a further deterioration of the robot velocity and the towing force as compared to the unidirectionally moving robots.

The insufficient clamping force produced by the electro-magnetically actuated reversing mechanism is the major reason for the slow forward and backward motion of the robot as well as for the poor propulsion force. In this regard it is decided to use an electro-mechanically actuating control system instead.

The design changes are illustrated in Fig. 9 and Fig. 10, presenting clearly the essential differences of this design as compared to the electro-magnetically one. The motor-controlled reversing mechanism uses the same friction rollers and roller carriers as in the electro-magnetically actuated one shown in Figs. 6 and 7. In the new design each pair of friction rollers are pushed against the wheels by using two separate control motors – 4, two pairs of a worm and worm gears 3, two sets of spur gears 5 connected in series to the spur rack - 2 fixed to a carrier - 7 as designated in Fig. 10. The first pair of gear trains consists of single-tooth worm and worm gear - 3 with the worm connected to the shaft of the control motor – 4 mating the worm gear 3, and a second pair of gears consisting of a spur pinion combined together with the worm gear and a spur gear 5 meshing the spur rack – 2. The latter is fixed to the carrier -7 of the friction rollers - 6 and - 8 as seen in Fig. 10. Both control motors are electrified concurrently to press the friction rollers either to the front wheels for forward motion or to the rear wheels for backward motion.

For example, when the pair of rollers - 6 are pressed against the front wheels a forward motion of the robot is achieved and vice versa by pressing the pair of friction rollers - 8 to the rear wheels a backward motion is obtained. Each pair of friction rollers are furnished with one-way rotating bearings to allow their rotation in the desired direction and block the rotation in the opposite one, so that to obtain a preferred motion of the robot.

In this design again two different power sources are employed; one with variable voltage to control the speed of rotation of the 6.8 Watt driving motor to achieve resonance in the propulsion mechanism (shaker) and separately the control motors are battery-powered with a supplied voltage of 14.4 Volts. During tests it is realized that the voltage of the battery is on the high side and need to be reduced to 10-12 Volts in order to optimize the clamping force of friction rollers against the wheels. The tests also revealed that if the contact force is too high the friction forces between the free rotating wheels and their axles become also high, creating large friction torques on the wheels, hence reducing the forward velocity of the robot.

To set the motion of the robot to forward or backward motion the control motors are powered at the same time in such a way either to push the friction rollers in forward or backward direction against the respective pairs of wheels by using simply an electric switch. As a result the motion of the robot is also changed as desired accordingly.

When analysing the performance of the robot, some of the difficulties associated with the electro-magnetically actuated propulsion mechanism in the previous design are also observed in this design. These are:

- The need for two different power sources of a suitable DC voltage.
- Since the wheel axes are rigidly fixed to the chassis they cannot follow the surface profile and hence failing to provide a friction contact with the ground.

- Lastly, only two out of four wheels is providing the necessary friction contact with the ground to achieve propulsion. It was also found that from time to time due to the rigid connection of the wheel's axes to the chassis only one out of the two wheels is in contact to the surface. This explains why the speed is reduced as compared to the speed of the one-way moving robots, where friction support is provided by all the wheels.

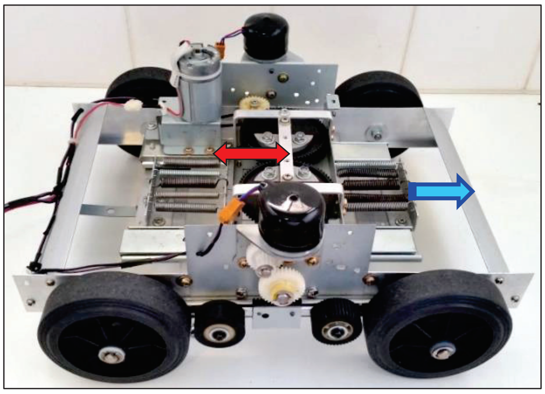

**Fig. 9.** The fourth prototype of the reversing robot furnished with a control motor-actuated reversing mechanism, achieving forward and backward motion, completed Jan. 2016

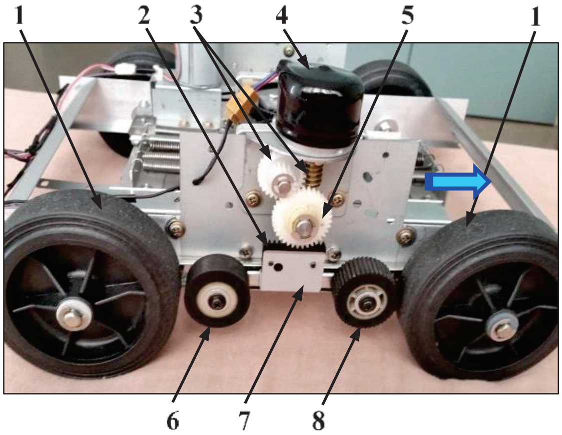


**Fig. 10.** Close view of a motor-activated reversing mechanism, where: 1- stands for free rotating wheels; 2 - rack; 3 - worm & worm gear set; 4 – control motor; 5 - spur gear set meshing the rack 2; 6 and 8 - friction rollers; 7- rack & roller carrier

In this regard, to improve the friction contact between the wheels and the ground a new design is suggested providing elastic suspensions of the wheels to the chassis. This was accomplished by elastically connecting each pair of the side wheels to the chassis, allowing them to copy the ground profile and let each pair of "driving" wheels to have the necessary friction contact with the ground. Obviously this is not the best solution to the above problems but at least better version of the previous design. The best solution could be each wheel to have individual elastic suspension as this is the case in all modern motor vehicles today.

Fig. 11 illustrates the elastic suspension of each pair of side wheels of the robot. Each pair is mounted on a separate carrier connected to the chassis by means of a bearing pivot. This allows the carrier to rotate partially about the chassis and therefore letting the wheels copying the ground, thus keeping them in permanent contact with the ground. This permits the robot to go through small obstacles still forcing the wheels to contact the ground.

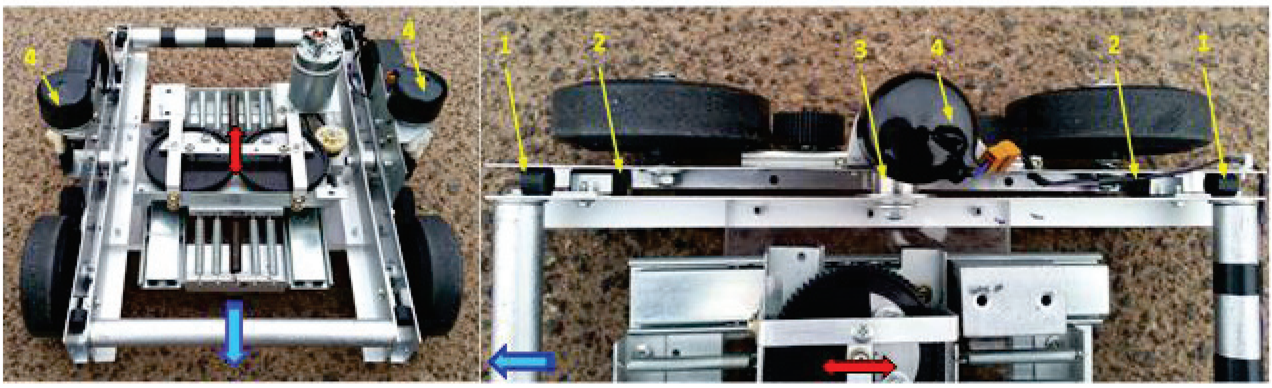


**Fig. 11.** The fifth prototype of the robot equipped with control motors - 4 aimed at achieving reversed motion, and a lateral-1 and vertical-2 rubber elastic suspension (as springs) allowing the wheels to partially rotate about pivot-3.

In addition to the benefit of the elastic suspension it is found that the new design provides an easy way to steer the direction of motion of the robot, by providing a separate power supply to each control motor. As a result the wheels can be engaged with friction rollers in pairs and also individually. For example: if the front left wheel and the rear right one is engaged with the friction rollers then this combination generates a pulsing turning moment forcing the robot to turn to the right. If an opposite combination is arranged then the robot will tend to turn to the left. During the process of turning, the other two wheels are completely free to rotate in any direction, so that they do not resist the turning process. This new vibration technique of steering a robot without using conventional steering mechanisms is simple, easy to achieve as compared to the conventional steering systems.

To avoid using two separate power units it is decided to use the power supply unit of the propulsion mechanism to govern both the driving motor and the control motors at the same time during the starting motion of the robot. Under these conditions the supply voltage will drop somewhat because of the increased power consumption and the contacting force between the friction rollers and the wheels will be moderate without increasing friction torques in the wheel's bearings as it was the case when using two independent power units. After that when the desired direction of motion is achieved the switch is to be set to its neutral position. This gives rise to the voltage supplied to the driving motor and the robot speed is increased to its maximum attained in resonance. To achieve this, each control motor has to be powered individually through a separate power supply switch.

## 2. Conclusions and recommendations

In this article the progress made in designing, constructing and testing of vibration-driven wheeled robots is presented and thoroughly discussed. Two different methods of reversing the vibration-driven robot are proposed and implemented in the robot design and their advantages and disadvantages are critically assessed. These are the electro-magnetically and electro-mechanically controlled reversing mechanisms. In addition to these designs, the wheels of the fifth version of the robot are equipped with elastic suspensions, allowing the wheels to copy the ground profile. This increases the robot performance avoiding the disadvantages of the rigidly fixed wheel shaft to the chassis, as it is the case with all previous designs.

It is acknowledged that the electro-magnetically controlled reversing mechanism is impractical as it requires two different power sources and the robot control and its performance is unsuccessful. The fifth robot design, which is equipped with electro-mechanically controlled reversing mechanism, is found to be much better than the third and fourth designs as its control is reliable and easy to use. It has superior benefits over the electro-magnetically controlled design because it uses only one power supply unit, offers a possibility of vibration steering, does not require a permanent power supply to control motors since the single start worm and worm gear train used in this design is self-locked when power is off, keeping the clamping force between rollers and the wheels constant.

All the three new reversible robots are tested and their advantages and disadvantages are considered. The fifth robot performance is the best as compared to the previous two reversible ones. It moves faster and reverses quickly since "driving" wheels are in continuous friction contact with the ground. As compared to one-way moving robots the fifth version still needs to be perfected by increasing the number of wheels in contacts with the surface.

The vibration-driven robots may be configured battery operated and to be radio-controlled so as to used in varieties of applications. They can carry cameras for daylight or night applications transmitting the information to a computer from where the operator can steer the robot in a real time.

With all these improvements and considering the advantages of vibration-driven robots being simple in design and easy to control, it is authors believe that their practical applications will be greatly broadened. They may be well appreciated in the chemical, nuclear, crude oil and mining industries, by the military in fighting terrorism and perhaps in the space industry as well.

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