Locomotion Gait Planning of Climber Snake-Like Robot

MOHAMMAD NEZAMINIA*, SALIM ABID TABASSUM**, AND IJAZ AHMAD CHAUDHRY***

RECEIVED ON 11.03.2012 ACCEPTED ON 18.09.2012

ABSTRACT

In this article a novel breed of snake-like climber robots has been introduced. Structure and operation of the first generation of snake-like climber robot "Marak I" has been discussed. The gait planning for two dimensional locomotion of a novel snake-like climber robot "Marak I" is presented. The types of locomotion investigated were rectilinear and wheeling gaits. The gaits of locomotion were experimented and their suitability for various applications has been mentioned. Some encountered practical problems plus solutions were addressed. Finally we found out that: the vertical motion was producing more fault than horizontal locomotion, and notably the fastest gait of locomotion was the wheeling gait.

Key Words: **Snake-Like Robot, Climber Robots, Rectilinear Gait, Wheeling Gait, Gait Planning.**

1. INTRODUCTION

The snake-like robots, can be defined and interpreted in different ways. Our definition of snake-like robots, with small variation, comes from Hirose, et. al. [1] description as those mobile robots that are made of abundant serially connected articulated portions, are inspired by snakes, and imitate one or several characteristics of snakes in nature. For example they may imitate the joint designs, (Liljebäck, et. al. [2]), or locomotion patterns (Ma, [3]). In this work we try to make a snake-like robot with an enhanced capability that is not available in nature (Nezaminia, [4]). In nature the snakes cannot climb the vertical flat surfaces with higher heights than their own maximum lift able lengths. We intend to add this climbing capability along a vertical surface to the snake-like robots and generate a new breed with the name of snake-like climber robots. There are several advantages linked to snake-like robots including, high stability, high terrain ability, high versatility and maneuverability of motion, high redundancy, high reliability, small cross-sectional size, and ease of sealing to name a few. Most of the snake-like robots built to date have a modular design. This modularity gives them higher precedence in the fields of maintenance, assembly and service than most of the conventional robots. Due to the mentioned advantages the snake-like robots can perform several tasks better than any other robot. This property will let them to be applicable in several areas such as: search and rescue (earthquake), surgery (minimally invasive surgery, laparoscopes and endoscopes), exploration, inspection (for hard-to-reach areas, cables, pipes and hazardous environments),

* Ph.D. Scholar, Department of Mechatronics & Control Engineering, University of Engineering & Technology, Lahore.
** Professor, Department of Mechanical Engineering, University of Engineering & Technology, Lahore.
*** Professor, Department of Mechatronics & Control Engineering,University of Engineering & Technology, Lahore.

firefighting, reconnaissance (military, police), espionage, stealth operation, and assembly to name a few. The snake-like robots that mimic the locomotion pattern of snakes can demonstrate one or several natural gaits of locomotion, which include lateral undulation, concertina, rectilinear, and sidewinding gaits. However, some of them are capable of undergoing non- snake gaits of locomotion as well. For example the wheeling, screwing, lateral rolling, wave rotor traveling, and flapping locomotion gaits are among the non-snake gaits of locomotion. Some other non-snake gaits are very similar to snake gaits, for example the caterpillar gait in worms is very similar to rectilinear gait. The climber snake-like robots may be capable of showing all the natural gaits of locomotion on horizontal surfaces but when facing the vertical flat terrain, the number of applicable natural gaits of locomotion will reduce. In this work the rectilinear gait (snake gait) and wheeling gait (non-snake gait) of locomotion has been used for both horizontal and vertical terrains. In the upcoming section there would be more explanation on these two gaits. If the work on snake-like robots be traced back, we find Gray, [5] who was the first to perform a real engineering work on snakes by exploring the natural gaits of locomotion through Newtonian laws. After his initial efforts in engineering field, Shigeo Hirose was the first who actually made the first truly snake-like robot (Hirose, [6]). His robot was called the ACM and was based on a model of lateral undulation gait. Later on, different dynamic models were created (e.g. the models of Liljebäck, et. al. [7] and Kane, et. al. [8]) and different types of snake-like robots were designed and constructed. However most of them were designed for terrestrial locomotion. Some of these snakes were capable of climbing different obstacles.

If we try to generalize, the climbing methodology in all the prior work can be divided into two categories. The first is the free climbing (Nilsson, [9]) in which the robot just uses its own joints for climbing. The second type is the anchoring/aid climbing in which the robot uses some kind of anchoring or support mechanism (For example the robot can use grooves, openings or poles as anchoring mechanism (Goldman, et. al. [10]). Although there has been so many snake designs that could follow one or both types of climbing categories (For example the pole climbing robot of Lipkin, et. al. [11]), but, up to now, there has not been any constructed snake-like climber robot capable of climbing a vertical flat terrain to a point higher than the self-length of the robot. In fact we believe that we were the first one to construct a snake-like climber robot [4]. We named the robot "Marak I". It was a robot with planar locomotion capability which incorporated the active suction cups in its anchoring mechanism. It was the first designed and constructed snake-like climber robot which incorporated these types of grippers in its anchoring mechanism. Here when we say snake-like climber robot, we mean a wall climbing robot that follows our definition of snake-like robot. From this point of view all other wall climbing robots which are not made of abundant serially connected articulated portions, or do not imitate the snakes (Lipkin, et. al. [12], Granosik, et. al. [13], Lal , et. al. [14]) will get excluded from our definition.

While we were working on our robot we were unaware of the fact that Zhang, et. al. [15], was working on the design of a climber caterpillar. Zhang, et. al. [15] up to the authors' knowledge, were unable to build the exact climber caterpillar they first proposed. Nevertheless they made some working climber robots based on their initial idea Wang, et. al. [16], and Li, et. al. [17]. What differentiated their work from ours was that their design incorporated the passive suction cups for climbing. However the passive suction cups have lots of issues regarding the flatness, surface finish, and porosity of the terrains thereby are less practical than our active suction cups. In addition to making the first robot with aforementioned properties, we were the first who examined and implemented the wheeling gait of locomotion for vertical climbing of snake-like robot. Although, Ma, et. al. [18] worked on climbing the slopes with snake-like configuration however he worked on lateral undulation gait. While our work was based on rectilinear as well as wheeling gaits from the snake and non-snake locomotion gait categories. In this paper we investigate the locomotion gait planning for both rectilinear and wheeling gaits.

2. ROBOT STRUCTURE AND OPERATION

The "Marak I" and its successor generation "Marak II" (yet to be constructed) consist of several modules. Each module itself consists of four major parts which are the actuation mechanism, anchoring mechanism, frame and joint mechanism, and sensory communication and power system. For "Marak I" the actuation mechanism consisted of the dc geared motor. Here by actuation mechanism we mean the dc motor actuation that is responsible for motion of robot's joints (This actuation mechanism is different from pneumatic actuation mechanism, vacuum actuation system or suction cup actuation that would be discussed later in this article). The anchoring mechanism consisted of a suction cup and its accessories. The frame and joint mechanism consisted of aluminum chassis and support parts plus the fittings and a bearing. The sensory, communication and power system consisted of associated wires and a potentiometer. Fig. 1 shows the major parts of one module of "Marak I". The modules could be placed in linear or zig-zag configuration. Fig. 2 demonstrates these two different placement methods. The zig-zag configuration was preferred because under the available physical constraints, it provided the minimum link length. The link length should be kept as minimum as possible. This, on one hand, will reduce the torque exerted on modules and on the other hand is an important factor on mobility increment of the robot in bounded spaces, Dowling, [19]. The "Marak I" was powered through variable dc power supply. Its motion was controlled by PC through a Control Board as shown in Fig. 3.

The Control Board consisted of Usbor Servo Controller and Power Isolation Board. The Usbor Servo Controller is a part of Robix Rascal set (Usbor-321 Rev: 0.0.2 was

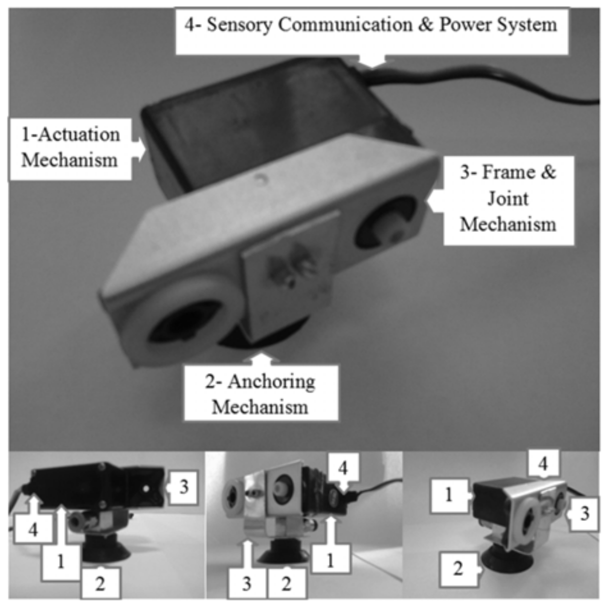

FIG. 1. MAJOR PARTS OF A MODULE OF "MARAK-I" ROBOT FROM DIFFERENT POINT OF VIEWS

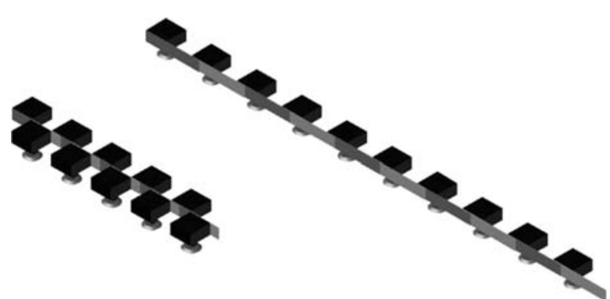

FIG. 2. MINIMUM POSSIBLE LENGTH FOR ZIG-ZAG AND LINEAR CONFIGURATIONS (TO ACHIEVE ROTATIONAL ASSUMPTIONS IN RECTILINEAR GAIT)

used here). It was used for controlling the servo motors and sending on/off signals to Power Isolation Board. The Power Isolation Board was used to energize solenoid control valves from an optically isolated power supply. The Usbor Control Board was programmed through Usbor dedicated programming environment. The programming environment included Usbor Nexway and Nexus programs which ran on Java Runtime Environment. The environment then sends/receives data through Usbor USB driver. This environment generates a point-to-point trapezoidal velocity trajectory by feeding different motion commands/parameters to its GUI (Graphical User Interface) e.g. position, velocity, and acceleration, to name a few. The motion commands are written in the GUI based on predefined Usbor script format. Fig. 4 demonstrates the robot's control architecture.

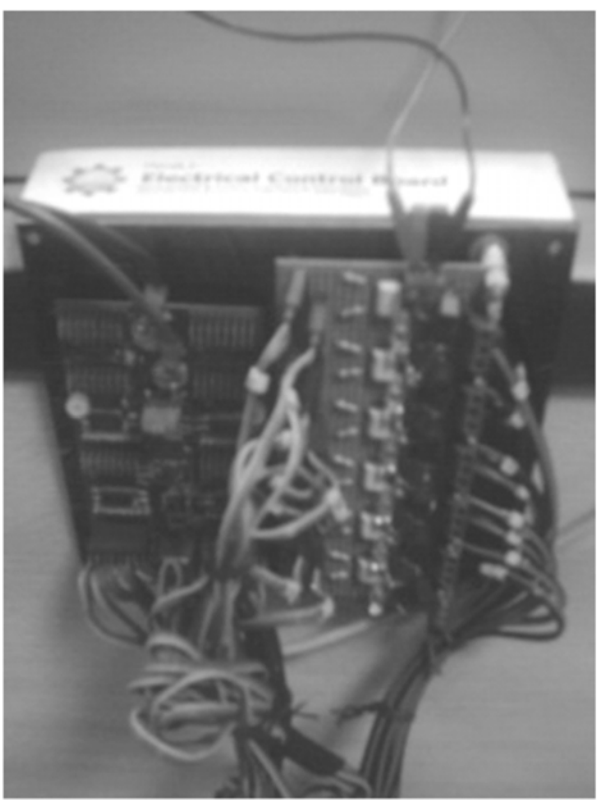

FIG. 3. "MARAK-I" CONTROL BOARD

A high pressure jet of air, while passing through ventury, created vacuum. The vacuum was applied to each module through pipes connected between ventury and the modules. Between supply and suction cups, the pneumatic actuation mechanism was implemented (consisting of directional and solenoid control valves), to connect/disconnect the vacuum lines (depicted in Fig. 5). With the help of these supplying, computing, actuating and communicating units the robot locomotion could be empowered, programmed and controlled. Fig. 6 shows the robot under operation between two steps of wheeling gait.

2.1 Model Demonstration

For ease of understanding each module was depicted as a bold line connected in the middle with series of lines resembling the shape of the inverted T. In fact the

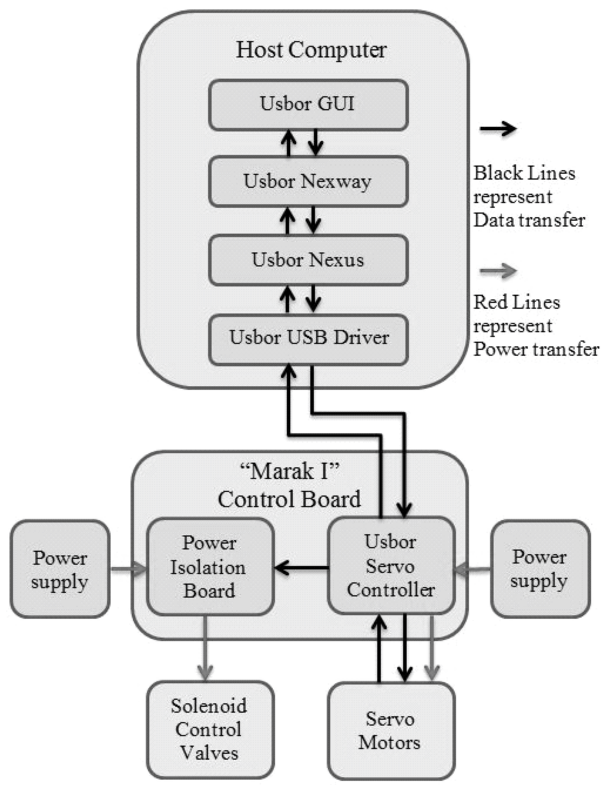

FIG. 4. "MARAK-I" CONTROL ARCHITECTURE

inverted T gives a simple demonstration of the suction cup. This representation gives better insight into the climbing methodology. Fig. 7 shows this demonstration technique.

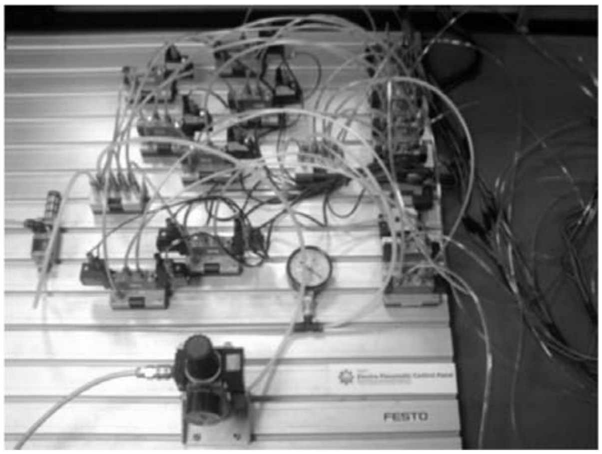

FIG. 5. "MARAK-I" PNEUMATIC ACTUATION MECHANISM

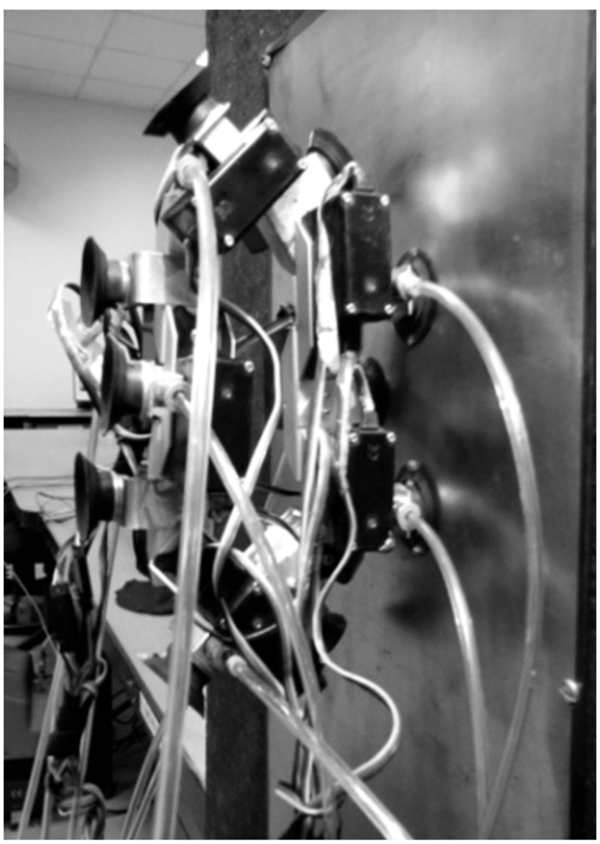

FIG. 6. "MARAK-I" DURING THE CHANGE OF STEPS OF WHEELING LOCOMOTION ON THE STEEL TEST BED

2.2 Gait Planning

Although "Marak I" was a two dimensional robot however several natural and non-natural gaits of locomotion could be implemented on it. Among these the rectilinear, concertina, inchworming, wheeling, or different combination of these gaits could be implemented. In

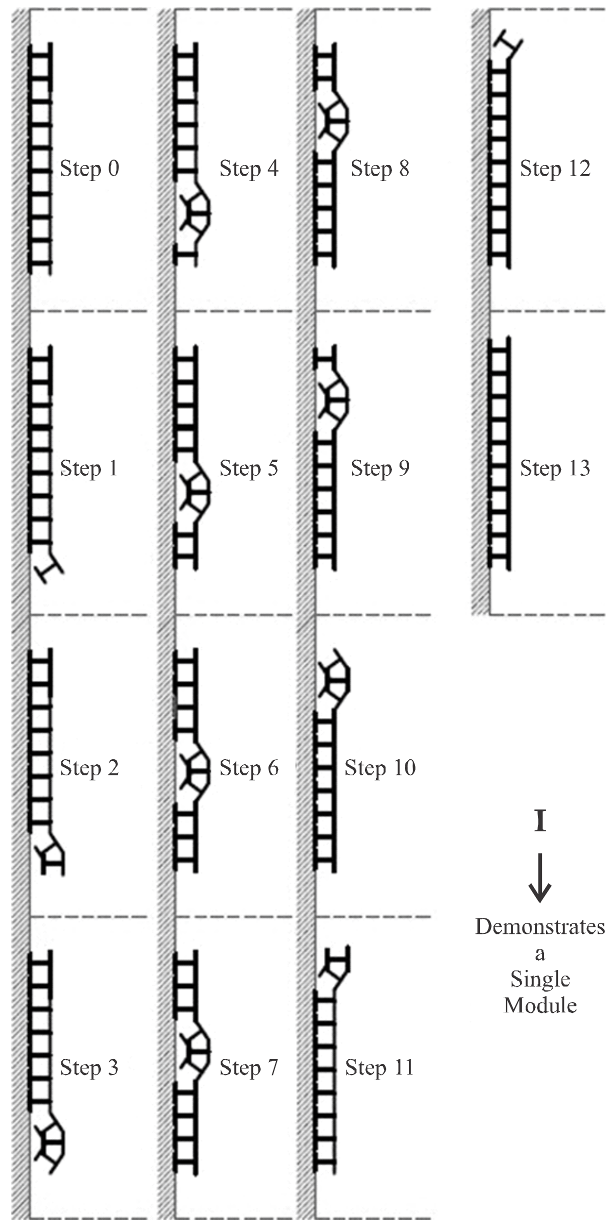

FIG. 7. THE DEMONSTRATION OF THE RECTILINEAR GAIT OF LOCOMOTION ON VERTICAL TERRAIN

between these gaits the rectilinear gait was selected to be the main gait of locomotion due to its high stability and low terrain slippage trend (Dowling, [19]). The gait was generated simply by passing a half wave from the tail of the robot to its head. When the half wave passes from the tail to the head, the associated links will be raised and lowered down accordingly and as a result the robot locomotes forward. The rectilinear gait presented here is based on the sequential motion representation by Merino, et. al. [20]. Fig. 7 demonstrates the rectilinear gait and its different sequences of motion on vertical terrain.

After implementing all the applicable gaits of locomotion on "Marak I" we became interested in the wheeling gait because we found it to be the fastest possible gait on vertical terrain (as a result the same gait is designed to be implemented on "Marak II"). Here in this paper we investigate these two gaits of locomotion. The wheeling gait will be formed if the head and tail of the robot be connected together in such a way that a loop of four distinct parts be made. The first and third parts are going to be equal in length and parallel to each other where the first would lie on the terrain and the third would be away from the terrain. The second and fourth parts are on two sides of the loop. This configuration is shown in Fig. 8. In fact the shape and locomotion of the robot will become similar to the shape and locomotion of a wheel. The wheeling gait was first implemented by Yim, [21-22]. Indeed the wheeling gait presented here is very similar to the Rolling-Track gait proposed by him. For controlling the gait of locomotion the Yim's GCT (Gait Control Table) [21] was used with a minor change. The GCT is a table having the numeric values of absolute rotations of each joint in degrees. The rows show the step number and the columns represent the associated module joint of the robot. In the GCT represented here the modules on each row, from the start to end, are synchronized. They start and stop at the same time. However, in the Yim's GCT the motion will start at the first segment of the row and ends at the last segment of the row.

The GCTs of the rectilinear and wheeling gait is depicted in Tables 1-2 accordingly. These control gaits have been considered for implementation with and without the actuation of the suction cups on horizontal terrain and with the actuation of suction cups on the vertical terrain.

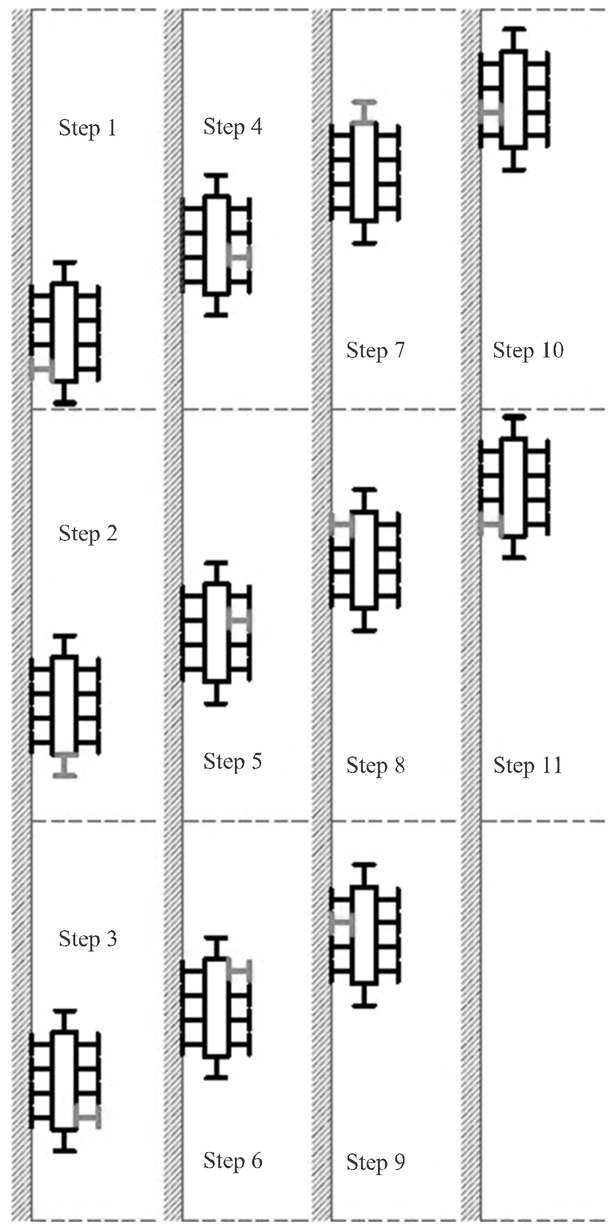

FIG. 8. THE WHEELING GAIT ON VERTICAL TERRAIN

It should be mentioned here that while the observer is faced towards the front view of the servo the plus sign (+) indicates the clockwise rotation and minus sign (-) shows the counter-clockwise rotation. The servos have been assembled in such a manner that the home position (zero) of the servos is at the middle of their rotational domain. By our convention in rectilinear configuration the joints are numbered from the lowest joint, as first, to the highest joint, as last, on vertical terrain. While on the horizontal terrain the numbering is from the right to the left for moving from right to left and vice versa (for left to right motion).

TABLE 1. THE RECTILINEAR GAIT OF LOCOMOTION

Step Number	Rotation of Module Number (In Degrees)								
	1	2	3	4	5	6	7	8	9
0th Step	0	0	0	0	0	0	0	0	0
1st Step	-35	0	0	0	0	0	0	0	0
2nd Step	+35	+35	0	0	0	0	0	0	0
3rd Step	+35	-35	-35	0	0	0	0	0	0
4th Step	-35	-35	+35	+35	0	0	0	0	0
5th Step	0	+35	+35	-35	-35	0	0	0	0
6th Step	0	0	-35	-35	+35	+35	0	0	0
7th Step	0	0	0	+35	+35	-35	-35	0	0
8th Step	0	0	0	0	-35	-35	+35	+35	0
9th Step	0	0	0	0	0	+35	+35	-35	-35
10th Step	0	0	0	0	0	0	-35	-35	+35
11th Step	0	0	0	0	0	0	0	+35	+35
12th Step	0	0	0	0	0	0			

TABLE 2. THE WHEELING GAIT OF LOCOMOTION

Step	Rotation of Module Number (In Degrees)									
Number	1	2	3	4	5	6	7	8	9	10
1st Step	+90	-90	0	0	0	-90	+90	0	0	0
2nd Step	+90	0	0	0	+90	-90	0	0	0	-90
3rd Step	0	0	0	-90	+90	0	0	0	+90	-90
4th Step	0	0	+90	-90	0	0	0	-90	+90	0
5th Step	0	-90	+90	0	0	0	+90	-90	0	0
6th Step	+90	-90	0	0	0	-90	+90	0	0	0
7th Step	+90	0	0	0	+90	-90	0	0	0	-90
8th Step	0	0	0	-90	+90	0	0	0	+90	-90
9th Step	0	0	+90	-90	0	0	0	-90	+90	0
10th Step	0	-90	+90	0	0	0	+90	-90	0	0
11th Step	+90	-90	0	0	0	-90	+90	0	0	0

On the wheeling gait the first joint is situated between the lowest connected module to the wall, pink module depicted on Fig. 8, and its counter clockwise neighbor. The numberings continues in the counter clockwise manner. For horizontal wheeling locomotion the first joint for moving right to left would be between the first module on the right side and its counter clockwise neighbor. For moving from left to right, the vice versa is employed. Although so many configurations were possible with the wheeling gait however by considering the limitation of rotation on the modules of robot the optimum configuration with respect to detaching moment arm and deflection of suction cups were achieved under the depicted wheeling configuration of Fig. 8. There are so many possible angular configurations for rectilinear gait as well however, the angle of 35 degrees was chosen because by going a little bit beyond this angle, in this gait, the suction cups of the module and its second consecutive module will touch each other. It should be emphasized here that 35 degrees limitation will not occur in wheeling gait. Because due to the zig-zag shape of the robot, gait design, and our convention of plus/minus sign, the modules are able to go to the mentioned plus or minus 90 degrees in wheeling gait. As it can be seen from Table 2, during each step of the gait just four joint angles are going to vary. If the rest of the joints of the robot be locked during transition from one step to other a simplified configuration which resembles the four-bar mechanism will be obtained.

3. EXPERIMENTATION

For experimentation the "Marak I" was placed on different test beds made of flat surfaced wood, steel, concrete and glass (mirror). The "Marak I" showed full climbing capability in all of them which proved the correct design of the robot. However, the best results, as expected, was obtained from the mirror terrain due to its smoothness characteristics. Both horizontal and vertical locomotions were performed on the aforementioned terrains.

Mainly due to the deflection of the suction cups the gaits of locomotion could not be followed exactly as the proposed GCTs. In fact by hit and trial methods the horizontal locomotion could be performed with a very minor deviation from GCTs, however the vertical locomotion had considerable deviation from the initial gaits of locomotion. Another issue which created some errors was the change of height of robot from un-actuated to actuated suction cup with 3.5 mm difference. All the associated errors plus the inaccuracy of the potentiometer sensor led the maximum deflection error of seven degrees. To compensate this problem some of the servos had to be rotated more. Another issue in practical experimentation was the bending of some of the suction cup's lips inward in some steps of different gaits of locomotion. For addressing this problem partial strengthening of the suction cups were employed. Although the errors were reduced but they were still present however the overall performance was fine. By experimenting the robot three times and each time with three consecutive gaits of locomotion under the same conditions we found out the average climbing velocity with single wave rectilinear gait on all testing beds to be1.06 mm/sec while the average velocity with wheeling gait was found out to be 10.08 mm/sec which is 9.51 times the rectilinear velocity. Wheeling gait showed the maximum deflection and was less stable compared to the rectilinear gait. Although our goal was not to build a fast robot however, we believe that the limiting factors affecting the robot climbing velocity were trajectory profile of servos, low servo power to module weight ratio, low servo torque to module inertia ratio, pulling force of the pipes and wires connected to the robot, deflection in suction cups (higher deflection will require the robot to move more for reaching the same point while it enforces more stabilization time after every sticking step), low negative pressure (lower pressures were also possible but not economical), low volume flow rates (higher volume flow rate were achievable but not economical), leakage from suction cups, use of directional control valves plus solenoid control valves instead of direct use of vacuum solenoid valves for vacuum actuation system, high friction in between robot parts and low thermal capacity of servos.

4. CONCLUSION

The "Marak I" was implemented on different terrains with different gaits of locomotion and showed the full climbing capability. The gaits of locomotion were planned and the robot implemented these for traversing the terrains. The kinematic, static, and dynamic modeling plus mathematical simulation is presented in a separate (to be published) paper. By comparing the results obtained from the experimentation we get to the following conclusions that: from the stability and deflection point of view the rectilinear gait showed the best results. As it was expected, from the speed point of view the wheeling gait showed maximum speed of locomotion among all the applicable gaits of locomotion on "Marak I" with almost 10 times the locomotion speed of the rectilinear gait. Finally for applications where the stability is the main concern, the rectilinear gait should be selected while for the applications where the speed of locomotion is the main issue, the wheeling gait should be implemented.

ACKNOWLEDGEMENT

The authors would like to thank the Internal and External Reviewers of this paper for their reviews, and helps.

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