

Kinematic Modeling and Analysis of a Serial-Parallel Field Robot with Variable Structure

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ABSTRACT

This paper addresses modeling and kinematic analysis of a serial-parallel structure-variable field robot which based on double spirals. Although a few researchers have studied on spiral propulsion mechanism, it is observed in our previous work that the spiral can move forward between gaps of plants and damages to the plants are very little. It can be used to carry measurement devices on investigation of the current state of wetlands. The robot consists of two pairs of spiral pipes and eight 4-DOF manipulators whose grippers handle the spiral pipes. Structure and main features of this double spiral propulsion robot are presented in this paper. The kinematic relations among manipulator's components are established through D-H method and walking plan is illustrated. To assure normal operation of this spiral propulsion mechanism, the forward and inverse kinematics analyses are presented.

Keywords: serial-parallel robot, kinematic, spiral

INTRODUCTION

The phenomenon that the area of wetlands reduces is becoming one of the major environmental conservation concerns. The project of the nature restoration has been started to protect and regenerate wetlands. First of all, the investigation of the current state and its degradation trend of the wetlands are critical to the project. Many efforts are made for field surveys by now. However, locomotion mechanism is necessary because it is hard for people to walk in vast uneven wetlands with many measuring instruments.

Many researchers focus on the development and researching of locomotion mechanisms. And one of the most important trends of the past decade has been the increased use of mobile robots in rough, unstructured terrain, such as

underground mines, forests, disaster sites, and planetary surfaces. Unstructured environments are often harsh, dangerous, or inaccessible to humans, and thus motivate the use of robotic systems. Numerous studies on mobile robots have been reported. A robot designed for exploration of volcanic craters (Estremera et al., 2009), robotics designed in hazardous fields (Lee et al., 2003), (Reis et al., (2007), and robotics in irregular terrains. (Freitas et al., 2009) and (Bouton et al., 2009). But the traditional locomotion mechanisms are not suitable to move in wetlands because of damage to the plants. Consequently, the most significant challenges for the field surveys focus on the development of locomotion mechanism to carry measuring instruments, which suppress damages of the vegetations and do not sink in mud.

Spiral propulsion mechanism is a kind of mechanism based on the coil-shaped spiral (Hanajima et al., (2008). Some research had been carried out on mobile-mechanism based on screw which is similar to spiral propulsion mechanism. Some of those mechanisms were designed to move on surface of lunar (Nagaoka et al., 2008, Hoshino et al., 2006, Nishida and Wakabayashi 2008 and Fields 1970). A mobile mechanism was designed for planetary exploration (Ishigami et al., 2007) and move on grounds rovers on loose soils (Wakabayashi et al., 2007, Neumeyer and Jones 1965). But there were few reports on spiral propulsion mechanism.

Fig.1 shows a concept diagram of a single spiral propulsion mechanism. Rotational torque exerted on the spiral can be converted into thrust force, which can promote the spiral to move forward. Because of multiple points of contact with the ground, its gravitational load is dispersed. And the spiral is also supported by branches or stem of plants, it is not easy to fall into mud. Furthermore, the spiral moves forward between gaps of plants, therefore damages to the plants are very little (Qunpo et al., 2010).

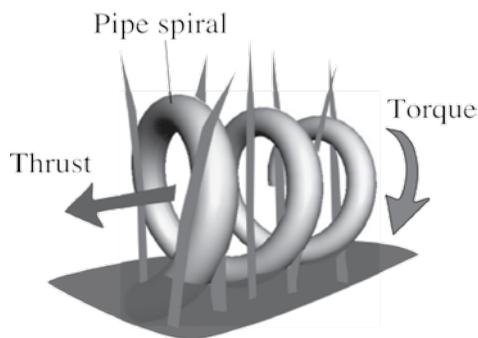


Figure 1. Diagram of a proposed spiral propulsion mechanism.

A prototype of the single spiral propulsion mechanism had been manufactured and tested on wetland. The spiral could move forward along the center axis as expected. But according to the experimental results, the spiral tends to generate significant frictional force on the ground when it rotates. If the load is

heavy, it must become difficult for the spiral to rotate. In order to overcome this difficulty, a double spiral propulsion (DSP) robot has been proposed (Hanajima et al., 2009). The foundational concept design is briefly introduced in this study.

MODEL OF THE ROBOT

Model of the Mechanism

The proposed DSP robot consists of platform, manipulators and spirals as shown in Fig.2. It has eight manipulators, which on the right-side and left-side of the platform viewing on the moving direction, sequentially numbered M1 to M4 and M5 to M8 respectively. One group of M1 to M4 connects the platform and two spirals on right side. And the other group of M5 to M8 left two spirals symmetrically. Two spirals in a group align on a central axis and mesh the other.

There are two kinds of manipulator: supporting manipulator and grasping manipulator which are same in structure but different in size and weight. M1, M4, M5 and M8 are supporting manipulators which are used to support the platform when spirals are grasped and derived to rotating forward. M2, M3, M6 and M7 are grasping manipulators which are used to grip the spiral up and drive the spiral to rotating forward.

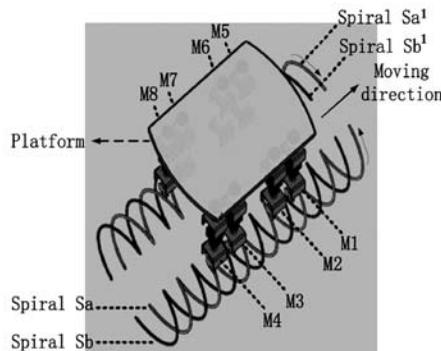


Figure 2. Symbolic structure of the robot.

Structure of the Manipulators

The coordinate systems at each joint of the manipulator are defined as Fig.3. There are 3 revolute joints and 1 prismatic joint. The origins of the first three coordinates are located on the same point, i.e. 0th, first and second coordinate frame. Third coordinate frame is defined at the center of the third revolute joint. Fourth coordinate frame is defined at the point where the grasper holds the spiral.

The DH parameters are shown as Table 1. The length g is a distance between the origin of third coordinate frame and fourth coordinate frame.

In addition, the structure of grasper in manipulator is presented in Fig.4. The wheel installed on the upper of the grasper is powered by an electric motor

and rotates the grasped spiral around its central axis. Fig.4 (a) and Fig.4 (b) are front view and backing view respectively when the grasper is in release position. In Fig.4(c) and (d), the two wheels installed in the behind can be moved up so that the spiral is tightly grasped.

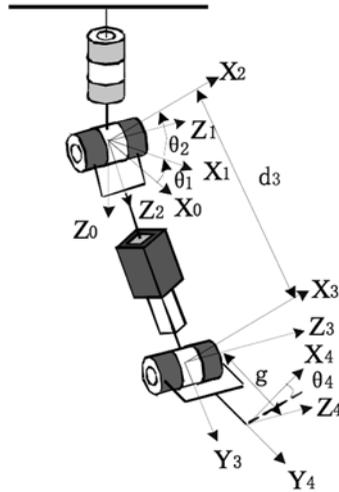


Figure 3. Coordinate systems on the joints.

Table 1. DH parameters for each link.

Link No.	i	a_i	α_i	d_i	θ_i
1		0	$\frac{\pi}{2}$	0	θ_1
2		0	$-\frac{\pi}{2}$	0	θ_2
3		0	$\frac{\pi}{2}$	d_3	0
4		g	0	0	θ_4

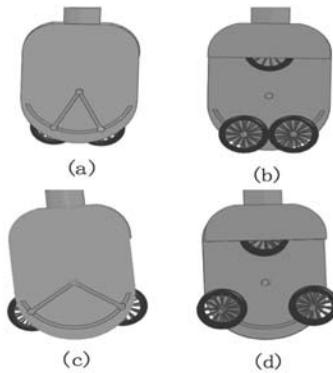


Figure 4. Concept of the grasper.

Structure of the Spiral

The spiral is made by curving the aluminum pipe of 32 mm in the diameter and 2 mm in the thickness in shape of spiral as shown in Fig.5. The outside diameter of the spiral is 500 mm, the rolling number, 7, pitch of screw thread, 150 mm, and the total length, 1050 mm.

Sequence of Spirals

This subsection explains the motion sequence of spirals as shown in Fig.5. The supporting spiral Sb on the right side and Sb' on the left side remain static to support the platform during the first step. Then the moving spirals Sa on the right side and Sa' on the left side are elevated by the grasper to reduce the frictional force between the spiral and the ground. Next, the spirals are rotated toward the traveling direction. Finally, the rotated spirals are placed on ground. And then the supporting spirals and the revolution spirals are alternated to each other.

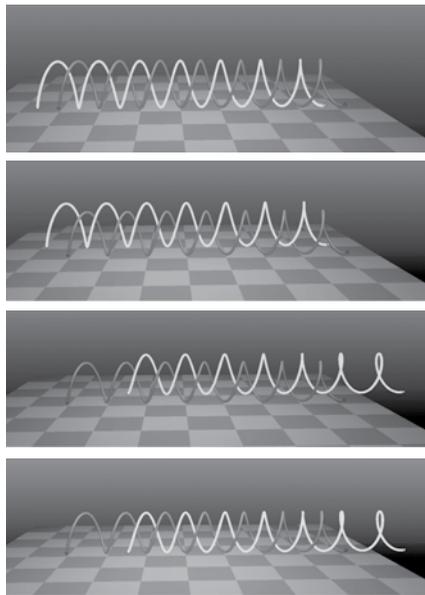


Figure 5. Motion sequence of spirals.

Locomotion Procedures

At the same time of locomotion of spirals, the robot itself moves on the spirals forwards. One cycle of the repeated locomotion procedures is presented in Fig.6. For the sake of convenience, the spirals are represented as straight lines, the supporting manipulators as thick-solid lines with a solid dot in the end, the grasping manipulators as thin-black lines with a circle in the end, and the platform as a rectangle. In the period of moving, the supporting manipulator is also presented as a thick-solid lines with a circle in the end.

At the moment of the supporting manipulator move from one spiral to another spiral, there need no-less than three supporting manipulators to keep

the whole system balance when it moving. As shown in Fig.6, one supporting manipulator can move forward, while the other three supporting manipulators are in static and keep the system in balance at the same time.

In the initial step 1, the spiral Sa and Sa' are grasped and lifted up by M2, M3 and M6, M7 respectively. In step 2, the spiral Sa and Sa' rotate around their axes by motors installed in each grasper of M2, M3 and M6, M7. After the spiral revolutes forward in a length of $2p$ (p is the pitch of screw thread), the spiral Sa and Sa' are lay down and place on ground, and the roll of manipulators is changed each other.

In the step 3, supporting manipulator M1 and grasping manipulator M7 move from Sb to Sa and Sa' to Sb' respectively so that their graspers follow the traveling direction and grasp next gripping points, while the other three supporting manipulators (M4, M5 and M8) are in static to keep the platform balance. After M1 and M7 finished their action, M1 starts to support the weights. M5 move from Sb' to Sa' and M3 move from Sa to Sb respectively so that their graspers follow the traveling direction and hold next gripping points, while the other three supporting manipulators (M1, M4 and M8) are in static to keep balance. This is the step 4.

In the step 5, M4 move from Sb to Sa and M6 move from Sa' to Sb' respectively. During this period, manipulators M1, M5 and M8 are keep static to keep balance.

In the step 6, M2 move from Sa to Sb and M8 move from Sb' to Sa' respectively. During this period, manipulators M1, M4 and M5 are keep static to keep balance.

In the step 7, all the manipulators shift the platform forward in a length of p .

In the step 8, same as step 1 and 2, spiral Sb and Sb' are grasped and lifted up by M2, M3 and M6, M7 respectively. Then spirals Sb and Sb' are rotated around its axis and move forward in a length of $2p$. After the rotation, the spiral Sb and Sb' are lay down and place on ground, and the roll of manipulators is changed each other.

The motion from step 9 to 12 is similar to step 3 to 6. Supporting manipulator move from Sa and Sa' to Sb and Sb' respectively, while grasping manipulators move from Sb and Sb' to Sa and Sa'. One support and one grasp manipulator can move in one step.

After the step 12 finished, the platform is shift forward in a length of p , 150 mm, same as step 7.

From step 1 to step 12 is one cycle of locomotion sequences, and these steps repeat continuously to keep the system moving.

KINEMATICS ANALYSIS OF THE MECHANISM

In this section, we derive the kinematic model of the double spiral propulsion robot.

Generally, robot structure can be serial, parallel or hybrid. Most of the

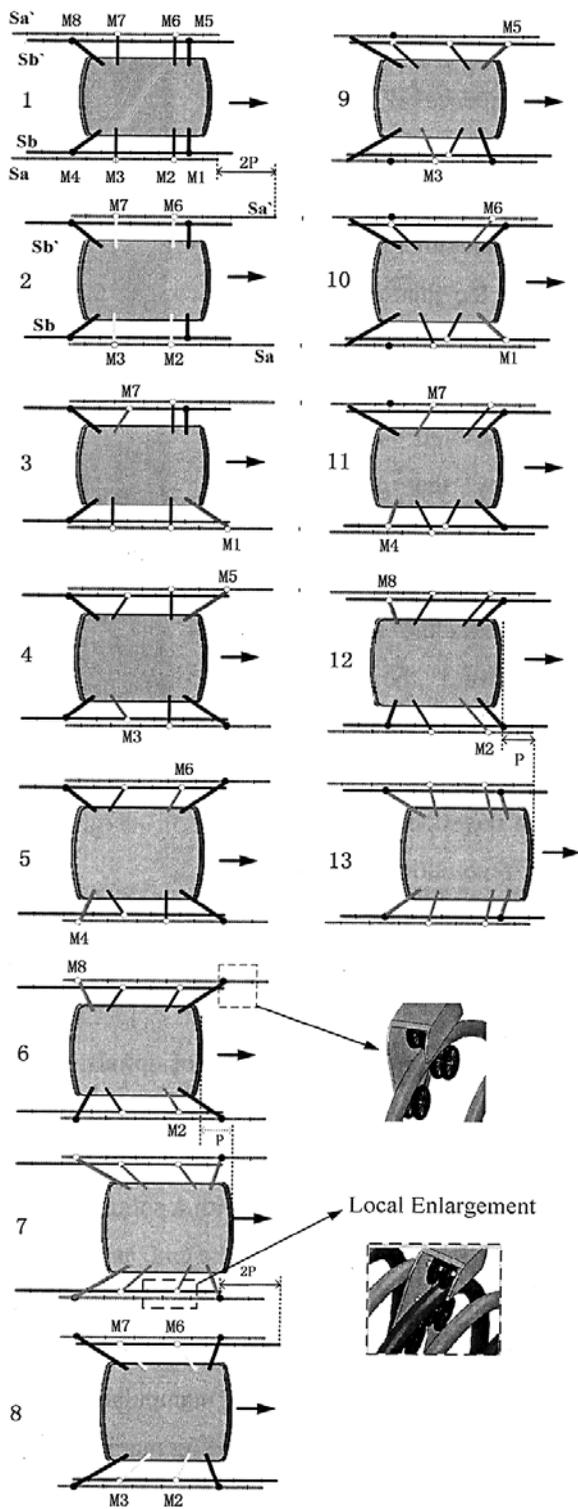


Figure 6. Locomotion procedures.

industrial robots, which are classified as serial robots, have open kinematic chain and serially connected links. A serial robot has a large working place, low cost, and great flexibility, while its stiffness, accuracy, and repeatability are relatively low. Sometimes, Serial robots are limited in the number of possible mechanical structures. But in some special situations, parallel manipulators can be an alternative to serial ones when the accuracy, high speed and stiffness are more important than large workspace. The parallel manipulator is a closed-chain mechanism which has two platforms (base and moving platform), connected together by at least two independent kinematic chains, with some advantages such as higher stiffness, accuracy, repeatability and greater load-to-weight ratio. A hybrid type manipulation system is a combination of closed-chain and open-chain mechanisms or it is a sequence of parallel mechanisms. It combines the performance advantages of parallel arm mechanism (e.g., high stiffness, high accuracy) with the large workspace of serial robot.

Numerous studies (Kerr 1989, Merlet 1992, Renaud et al., 2006, Zhang and Lei 2010, Chablat and Wenger 2003, Huang et al., 2004 and Alizade et al., 2008) on parallel robot have been reported since the first practical application which proposed by Stewart (1965) in 1965, considering kinematics, singularity, workspace, dynamics and design of parallel manipulators. In reference (Zhu et al., 2005), new structural formulas of parallel and serial platform Euclidean robot manipulators with variable general constraints are introduced. Tanev (2006) presents a kinematic analysis of a new type of hybrid (parallel-serial) robot manipulator which consists of two serially connected parallel mechanisms. A compounded serial-parallel wheeled mobile robot was elaborated in (Moosavian et al., 2005). And new method for structural synthesis of Euclidean platform robot manipulators with variable general constraints (EPRM) is presented in Alizade et al., (2008). To the best of our knowledge, no further insights into the analysis of the mechanism with variable structure between serial and parallel.

In current study, kinematics of a new structure-variable mechanism, which based on double spirals, is presented. As introduced in the walking procedures, all the manipulators work as serial structure with open kinematic chain and serially connected links, except step 7 and step 13. The kinematic analysis of the robot work as a serial mechanism have been introduced in Qunpo (2010), in which the detailed structure, coordinate system, and parameters of this mechanism are given. In this part, the kinematic analysis is presented when it work as a parallel mechanism.

In step 7 and 13, all the manipulators shift the platform, which is a moving platform in this period, to move forward in a length of 150mm. At the same time, all the spirals are being grasped by end-effectors of manipulator and cannot move because of frictions between ground and plants, which can be considered as an equivalent base platform, as shown in Fig.7. The mechanism works as a parallel robot with a moving platform, a base platform, and eight manipulators during those periods. As we all know, all the first revolute joints of manipulator R_{i1} ($i=1,2,\dots,8$) must be move on the same speed, and in the same direction at the same time.

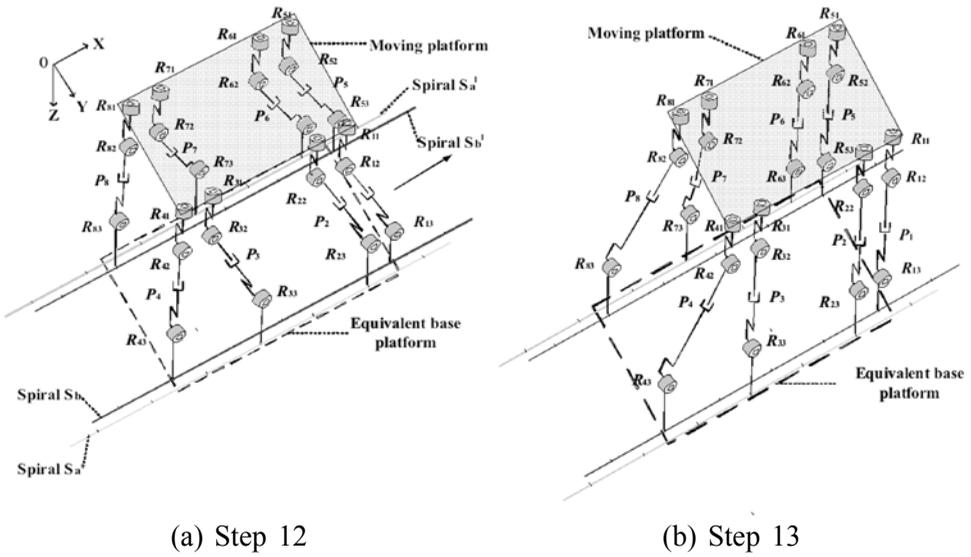


Figure 7. Configuration of the mechanism as a parallel robot when the platform moving from step 12 to step 13.

$$A_1 = \begin{bmatrix} \cos \theta_1 & 0 & \sin \theta_1 & 0 \\ \sin \theta_1 & 0 & -\cos \theta_1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

$$A_2 = \begin{bmatrix} \cos \theta_2 & 0 & -\sin \theta_2 & 0 \\ \sin \theta_2 & 0 & \cos \theta_2 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$$A_3 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$$A_4 = \begin{bmatrix} \cos \theta_4 & -\sin \theta_4 & 0 & g \cos \theta_4 \\ \sin \theta_4 & \cos \theta_4 & 0 & g \sin \theta_4 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

The homogeneous transformation matrix A_i ($i=1, 2, 3, 4$) between $(i-1)$ th link frame and i th link frame are as follows.
 In this period, the revolute joint R1 need not to perform any action. Therefore, the whole homogeneous transformation matrix T is as follows.

$$T = A_4 A_3 A_2 = \begin{bmatrix} R_4^0 & p_4^0 \\ 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} \cos \theta_2 \cos \theta_4 & -\sin \theta_4 & -\sin \theta_2 \cos \theta_4 & g \cos \theta_4 \\ \cos \theta_2 \sin \theta_4 & \cos \theta_4 & -\sin \theta_2 \sin \theta_4 & g \sin \theta_4 \\ \sin \theta_2 & 0 & \cos \theta_2 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

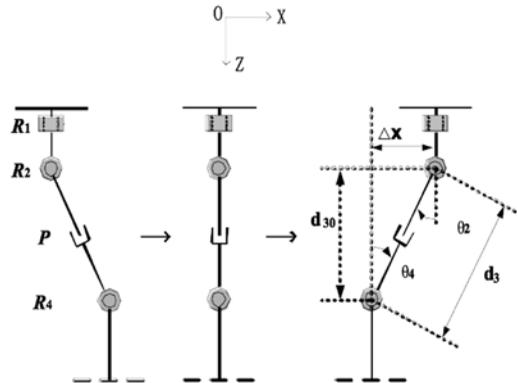


Figure 9. Geometry of manipulator from step 12 to step 13.

Inverse kinematics is to determination of joint variables in terms of the manipulator position and orientation. In our case the inverse kinematics analysis relies on the decoupling technique. As shown in Fig.8, the joint variables are given as follows.

$$\Delta X = d_{i30} * \tan \theta_{i4} \quad (6)$$

$$d_{i3} = \frac{\Delta X}{\sin \theta_{i4}} \quad (7)$$

$$\theta_{i2} = \theta_{i4} \quad (8)$$

Notion that $i = 1, 2, \dots, 8$. We can get the relation between speed of the moving platform and joint variables.

$$\dot{\Delta X} = \dot{d}_{i3} * \sin \theta_{i4} + d_{i3} * \cos \theta_{i4} * \dot{\theta}_{i4} \quad (9)$$

CONCLUSION

The graphical model of double spiral propulsion robot was proposed to fulfill environmental investigation in wetlands. The kinematic relations among manipulator's components were developed and the kinematic analyses were illustrated as a parallel mechanism. This robot has some advantages when moving on wetlands. Many challenges are remained to realize the robot in practice. Study on undergoing changes of the DSP robot's state as time evolves is also essential in the design, analysis, computer simulation and control of the system. Detailed mechanism and dynamic analysis are planned as future work.

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