

## Modeling of Serpentine Device Mechanics for Pipeline Inspection

Andrey U. Aleynikov, Andrey N. Afonin, Maria A. Sitnikova,  
Andrey R. Gladishev and A. Anastasiya V. Popova  
Belgorod State University, Pobedy St. 85, 308015 Belgorod, Russia

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**Abstract:** The researchers simulated the mechanical design of a snake-like diagnostic device by their own design. The proposed model can be used in the development of a robot movement control algorithms and its interaction with obstacles.

**Key words:** Snake-like robot, mathematical model, link, the center of weights, interaction

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### INTRODUCTION

Snake-like device are referred to a separate class of systems that can move almost along any rugged terrain due to the large number of freedom degrees. The use of such systems for diagnostic purposes to move the equipment along pipelines has many advantages, not achievable with other transportation options (Hirose, 1993; Aleynikov *et al.*, 2015). A significant number of freedom degrees requires a corresponding amount of executive units-servos and electronic modules serving them. It necessitates the development of complex control algorithms, based on well-formalized mathematical model of a system particularly in the context of interaction with obstacles.

In order to describe the kinematics of a snake-like diagnostic device using the approach that is used during the operation with multilink manipulators of robotic systems is Denavit-Hartenberg idea (Shahinpur, 1990). The mathematical relations between translational and rotational movements of kinematic chain adjacent links can be obtained with its help.

### MATERIALS AND METHODS

The method consists in the presentation of the system of coordinates position in respect of each subsequent link relative to the previous one through the homogeneous transformation matrix with the dimension  $4 \times 4$ . Thus, using matrix calculations it is possible to obtain the coordinates of a predetermined point in the coordinate system of any link.

The device in question consists mainly of rotational joints with only one degree of freedom, in each of which an actuator excites a motion resulting in angular displacement of one link with respect to the previous one and therefore to the connection angle change.

Let's  $i = 1, 2, \dots, m$  is the index of the rotational joint coordinate system and the link number with which it is associated. In accordance with the rules of a coordinate system development, the axis  $Z_i$  is directed along the axis of the joint. Let's assign the axis  $X_i$  in the direction of the shortest distance between the coordinate systems of the neighboring joints, as well as perpendicular to the axis  $X_i$ . The axis  $Y_i$  is directed so that it is supplemented the axis  $X_i$  and  $Z_i$  to the right Cartesian coordinate system.

The angle between the adjacent links (connection angle) which is a variable is denoted as  $\theta$ . In terms of this approach, it is the angle by which the rotation of the axis  $X_{i-1}$  is necessary concerning the coordinate system of the previous link around the axis  $Z_{i-1}$ , to make it co-directional with the axis  $X_i$ .

Based on the fact that this device has no links with the translational motion, the parameters which are the characteristics of the joints (connected parameters) are the distance  $d_i$  (the offset along the axis  $Z$  between adjacent coordinate systems) the linear displacement  $a_i$  (the displacement along the axis  $X$  between neighboring coordinate systems) and the angular displacement  $b_i$  (the angle by which the axis  $Z_{i-1}$  should be rotated the axis  $X_i$  to make it co-directional with the same axis  $Z_i$  (the coordinate system followed after it).

Figure 1 shows the fragment of a snake-like robot 3D model with developed coordinate systems Denavit-Hartenberg. Let's perform the development of homogeneous transformation matrices which connect the right and  $i-1$  coordinate systems. Thus, it is possible to convert the coordinates of any point, for example determining the location of the mass center of a link, set in  $i$ th coordinate system into the coordinates of the same point with respect to  $i-1$  of coordinate system. In order to obtain the transformation matrix  $A_i^1$  that links the first and the second coordinate system it is necessary to perform the following steps:

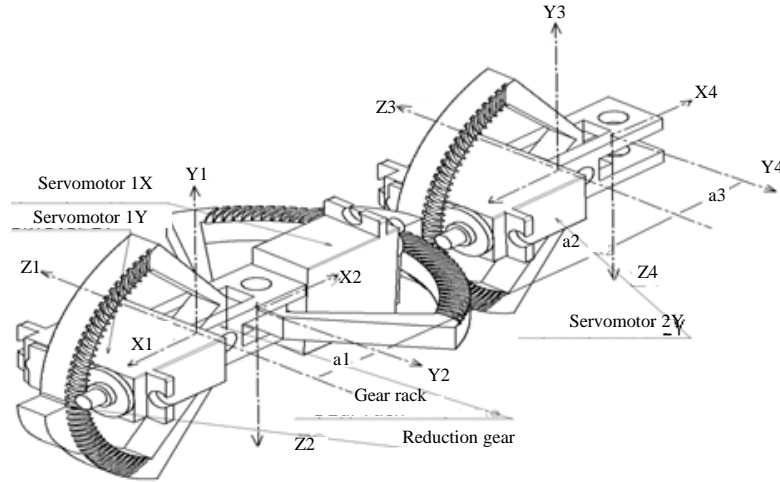


Fig. 1: A part of snake-like robot 3D model design with formed coordinate systems Denavit-Hartenberg

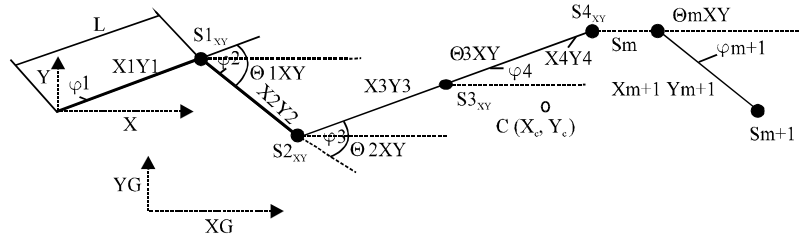


Fig. 2: Simplified planar schematic view of the kinematics of the snake-like device.

- The rotation by the angle  $\theta_{1xy}$  around the axis  $Z_1$  to make the axis  $X_1, X_2$  parallel ones
- The rotation around the axis  $Y_1$  by  $180^\circ$ , to make the axis  $X_1$  and  $X_2$  codirectional
- The shift along the axis  $X_1$  at the distance  $a_1$  to align the coordinate origins
- The pivot the axis  $X_1$  by the twisting angle  $b = 90^\circ$

In order to obtain the transformation matrix  $A_3^2$ , connecting the 2nd and the 3rd coordinate system it is necessary to perform the following operations:

- Turn by the angle  $\theta_{1xz}$  around the axis  $Z_2$ , to make the axis  $X_2$  and  $X_3$  parallel ones
- The turn along the axis  $Y_2$  by  $180^\circ$  to make the axis  $x_2$  and  $X_3$  codirectional ones
- The turn around the axis  $X_2$  by the twisting angle  $b = 90^\circ$  to make the axis  $Z_2$  and  $Z_3$  parallel and codirectional ones
- The shift by the distance  $A_2$  along the axis  $X_2$  to align the coordinate origins

Each of these operations can be described by one unified matrix of elementary rotation-shift and the product

of matrices will give a uniform matrix for the adjacent coordinate systems. The expression for the transformation matrix  $A_2^1$  has the following form:

$$A_2^1 = T_{z, \theta_{1xy}} T_{y, 180} T_{x, a_1} T_{x, b} \quad (1)$$

The expression for the transformation matrix  $A_3^2$  has the following form:

$$A_3^2 = T_{z, \theta_{1xz}} T_{y, 180} T_{x, b} T_{x, a_2} \quad (2)$$

It is not hard to see that for all other elements of a snake-like device the transformation matrices are calculated in a similar manner. Then, the resulting transformation matrix between coordinate systems of a head and a tail part  $A_{24}^1$  will be the following ones:

$$A_{24}^1 = A_2^1 A_3^2 A_4^3 A_5^4 A_6^5 A_7^6 A_8^7 A_9^8 A_{10}^9 A_{11}^{10} A_{12}^{11} A_{13}^{12} A_{14}^{13} A_{15}^{14} A_{16}^{15} A_{17}^{16} A_{18}^{17} A_{19}^{18} A_{20}^{19} A_{21}^{20} A_{22}^{21} A_{23}^{22} A_{24}^{23} \quad (3)$$

One of distinguishing features concerning the device in question from a multilink manipulator is that it does not

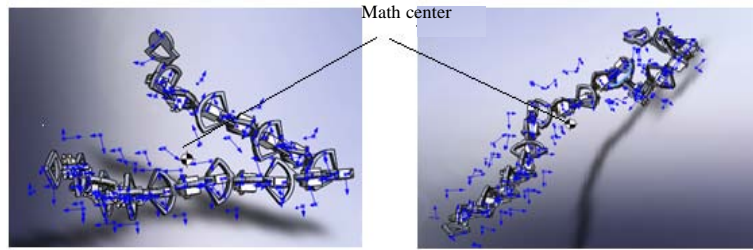


Fig. 3: Location of mass center

have a stationary (fixed) coordinate system, which allows it to move. A simplified two-dimensional schematic representation of a snake-like device kinematics (links and joints responsible for the movement only along XY plane are presented) is shown on Fig. 2.

### RESULTS AND DISCUSSION

The analysis of a snake-like device movement is convenient through a center of masses. The centers of masses concerning individual units located at the points with the coordinates  $x_1, y_1, \dots, x_{m+1}, y_{m+1}$  (in the global coordinate system). The center of mass of all planar device masses in the global coordinate system is represented in the point C ( $x_c, y_c$ ). However, actually, the center of masses is located in three-dimensional space and has also the coordinate Z. The location of the center of masses is also important from the viewpoint of new types of movement synthesis and the compensation of the effects arising from the damage of any servo or servos, when a motion control task is added with the task of motion direction correction.

The joint rotation angles through the built-in servos (for the plane XY) is described by the variable  $\theta_{xy}$ . The rotation angles of joints by the built-in servos (for XZ plane) are described by the variable  $\theta_{xz}$  (they are not shown on the Fig. 2). The rotation angles of links in the global coordinate system are described by the variable  $\varphi$ . L is a link length.

Taking into account these relations for Denavit-Hartenberg presentation the coordinate centers of each joint masses can be obtained with respect to any snake-like device joint.

A snake-like device has no well-defined orientation in a space during its movement (the direction of movement) due to a large number of freedom degrees. However, it is possible to calculate its average value directly using each two axes for each joint (Liljebäck, 2013; Kimura *et al.*, 2006):

$$\bar{\theta}_{xy} = \frac{\sum \theta_{xy_i}}{N_{xy}} \quad (4)$$

Where:

$i = 1, \dots, m$  Coupling index in XY plane

$N_{xy}$  = Number of couplings XY

$$\bar{\theta}_{xz} = \frac{\sum \theta_{xz_i}}{N_{xz}} \quad (5)$$

Where:

$i = 1 \dots k$  coupling index in XZ plane

$N_{xz}$  = Number of XZ couplings

The coordinates of the entire device mass center, calculated in the following way:

$$x_c = \frac{\sum x_i}{N_c}; y_c = \frac{\sum y_i}{N_c}; z_c = \frac{\sum z_i}{N_c} \quad (6)$$

Where:

$\Sigma$  = Link index

$N_c$  = Number of links

The calculation is performed sequentially by joints in XY and XZ plane. The location of mass centers (a circle with alternating white and black elements) for several configurations of a snake-like device is presented on Fig. 3.

### CONCLUSION

The mathematical modeling was performed concerning the mechanics of a snake-like diagnostic device. The proposed model can be used during the development of a robot movement control algorithms in the space and its interaction with obstacles. The fundamental difference of Denavit-Hartenberg presentation for the analysis of serpentine robotic devices from multilink manipulators is the presence of a rigid connection with a fixed base among the latter. In the case with serpentine robots such bond is absent but some of its similarity can be obtained by the displacement of the center of masses to a desired location of a virtual securing.

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**REFERENCES**

Aleynikov, A.Y., A.N. Afonin, A.R. Gladyshev and A.D. Novoseltsev, 2015. Realization of an autonomous mobile snake-like robot design. *Mater. Intl. Sci. Tech. Conf. Extreme Rob.*, 2015: 250-253.

Hirose, S., 1993. *Biologically Inspired Robots: Snake-Like Locomotor and Manipulator*. Oxford University Press, Oxford, England, ISBN:9780198562610, Pages: 220.

Kimura, H., K. Tsuchiya, A. Ishiguro and H. Witte, 2006. *Adaptive Motion of Animals and Machines*. Springer, Tokiyo, Japan, ISBN:978-4-431-24164-5, Pages: 296.

Liljeback, P., 2013. *Advances in Industrial Control*. Springer, London, England, Pages: 280.

Shahinpur, M., 1990. *Robotics Course*. University of Pennsylvania, Philadelphia, Pennsylvania, Pages: 527.