Contribution to the Solving of the 3D Manipulator Mechanism of the Military Robotic System

Radek DOSKOČIL[a], Jiří FISCHER[b] and Václav KŘIVÁNEK[c]

[a] Department of Air Defence Systems, University of Defence, Brno, Czech Republic, e-mail: radek.doskocil@unob.cz
[b] Department of Air Defence Systems, University of Defence, Brno, Czech Republic, e-mail: jiri.fischer@unob.cz
[c] Department of Air Defence Systems, University of Defence, Brno, Czech Republic, e-mail: vaclav.krivanek@unob.cz

Abstract

The article deals with the development and design of manipulator body for mobile military robotic system that has been designed to Department of Air Defence. Own manipulator mechanism has concept of the 3D spherical type manipulator. The entire mechanical part is constructed on the basis of three relatively independent motion modules, each fitted with an individual drive DC motor with gear. The paper also contains the calculation of kinematic variables by means matrix method.

Key words: 3D, Robotic, Manipulator, Mechanism, DC Motor, Matrix.

1. Introduction

Our Department of Air Defence System has been interested in wheeled robotic chassis that solved as autonomous mobile system since 2013 or sooner. Within the scope of the development of this robot system the mechanical platform to control sensors was designed and constructed, Fig. 1. It was solved as an independent modular system that can be quickly mounted to chassis.

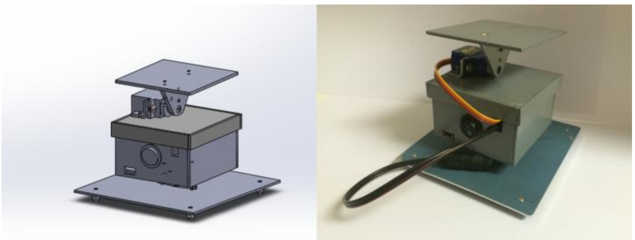

Fig. 1. The model and real mechanical platform to control sensors

Nowadays a system for handling objects close to the chassis has been solved. It would be solved on the same principle as sensor platform. This means that a handler should be independent module that would be put on or take off to chassis on short time.

The purpose of the handling system is to increase the robot throughput in a real environment by means of removing minor obstacles. The concept goes as follows. Robot with help sensors detects obstacle (some object) and evaluate the possibilities how to overcome it. If robot did not find the possible way to overcome obstacle, it will carry or push obstacle out of the trajectory of movement. If this possibility is not real, the robot will try to find appropriate trajectory to go round the obstacle. We add that way of make-decision and control of chassis is not topic of this article but configuration of mechanical layout of manipulator.

During designing manipulator the kinematic characteristics the analysis of existing system with similar handling abilities was done. High manipulating ability of system with minimum movement elements and control simplicity were follow. Also the implementation by own resources of department, finances and availability of proposed components were taken account.

After analyses and consideration of all mentioned conditions we decided:

- The handling system must be able to manipulate to object in the 3D space. To be able to grasp the body in the vicinity of the contour of its chassis, we must choose a spherical arrangement of the kinematic structure of the mechanism.
- The spherical arrangement runs to the configuration of the handling system to consist from three rotary motion units, each with an independent (separate) propelled (i.e. three-stage handling system), see Fig. 2.
- Usage of sliding motion units appears as unsuitable for this case. It would increase the range of the handling system, but their use has a number of manufacturing and operating difficulties, and also it would increase the economic cost.
- For the spherical type of handling system be true $\bar{R}_z - \bar{R}_x - \bar{R}_x$.

  Where $\bar{R}_z$ expresses rotary movement unit with rotation about an axis z_1 and $\bar{R}_x$ are rotary movement units with rotation about an axis x_2 a x_3. The directions of axis are shown in Fig. 2.

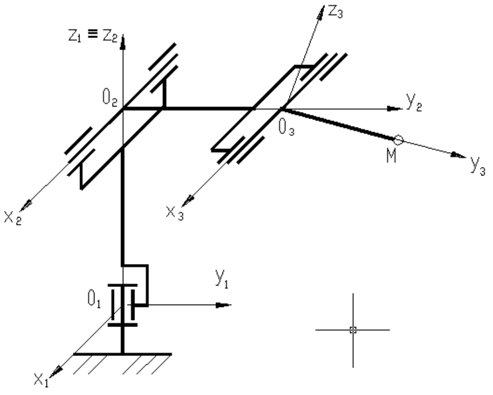

Fig. 2. The spherical kinematic string

2. Determination of Kinematic Quantities

Own solution of kinematic quantities is done for the endpoint handling arm, i.e. for point M, see Fig. 2. Identification of all the values used for the calculation is shown in this diagram.

Matrix method of calculation of kinematic quantities was used to solve robot leg kinematic; it is well e.g. in [1] or [2]. Solution analysed quantities were done in software Matlab. For the calculation the dimensions of the individual parts of the legs are chosen as follows: G = 0.14 m, H = 0.028 m, K = 0.3 m, L = 0.3 m, n = 0.012 m. The ranges of angles at each joint are: $\varphi_{21} = \pm 150$, ψ_{32} = -20°, +40°, ϑ_{43} = ±60°. A kinematic chain is drawn in the position where the angles of arms regarded as zero (in the basic position of the mechanism). The sense of determination is shown in Fig. 3.

Figure labels should be legible, approximately 8 to 12 point type.

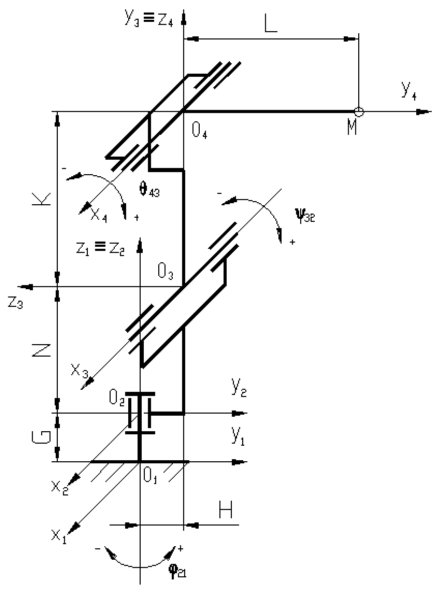

Fig. 3. Computational model of handling system

a) Position

The final position of the end point M of handling arm (relative to the origin of the reference coordinate system $O_1x_1y_1z_1$) is:

$$\bar{\mathbf{r}}_1^{M} = \mathbf{T}_{41} \cdot \bar{\mathbf{r}}_4^{M} = \mathbf{T}_{21} \cdot \mathbf{T}_{32} \cdot \mathbf{T}_{43} \cdot \bar{\mathbf{r}}_4^{M} . \qquad (1)$$

Where $\mathbf{T}_{41}$ is total transformation matrix of motion of the entire system and $\mathbf{T}_{21}$, $\mathbf{T}_{32}$ and $\mathbf{T}_{43}$ are transformation matrixes of motion of the adjacent bodies. For the choose option of handling system the shapes of these matrixes are (see Fig. 3):

$$\mathbf{T}_{21} = \begin{bmatrix} \mathbf{S}_{21} & \mathbf{r}_1^{O_2} \\ \mathbf{0} & \mathbf{1} \end{bmatrix}, \ \mathbf{T}_{32} = \begin{bmatrix} \mathbf{S}_{32} & \mathbf{r}_2^{O_3} \\ \mathbf{0} & \mathbf{1} \end{bmatrix}, \ \mathbf{T}_{43} = \begin{bmatrix} \mathbf{S}_{43} & \mathbf{r}_3^{O_4} \\ \mathbf{0} & \mathbf{1} \end{bmatrix}, \qquad (2)$$

Relevant direction matrixes according to coordinate systems are:

$$\mathbf{S}_{21} = \begin{bmatrix} \cos\varphi_{21} & -\sin\varphi_{21} & 0 \\ \sin\varphi_{21} & \cos\varphi_{21} & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad \mathbf{S}_{32} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\psi_{32} & -\sin\psi_{32} \\ 0 & \sin\psi_{32} & \cos\psi_{32} \end{bmatrix},$$
$$\mathbf{S}_{43} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\vartheta_{43} & -\sin\vartheta_{43} \\ 0 & \sin\vartheta_{43} & \cos\vartheta_{43} \end{bmatrix}. \qquad (3)$$

Position vectors of individual coordinate systems are:

$$\mathbf{r}_1^{O_2} = [0, \quad 0, \quad G]^T, \ \mathbf{r}_2^{O_3} = [0, \quad H, \quad N]^T, \ \mathbf{r}_3^{O_4} = [0, \quad K, \quad 0]^T$$

$$\mathbf{r}_4^{M} = [0, \quad L, \quad 0]^T . \qquad (4)$$

After putting these values to Eq. (2) and next to Eq. (1) to obtain the courses of the point positon M:

$$\mathbf{r}_1^{M\prime} = \begin{bmatrix} -L\cdot\sin\varphi_{21}\cdot\cos\psi_{34}\cdot\cos\theta_{43} + L\cdot\sin\varphi_{21}\cdot\sin\psi_{34}\cdot\sin\theta_{43} - K\cdot\sin\varphi_{21}\cdot\cos\psi_{32} - H\cdot\sin\varphi_{21} \\ L\cdot\cos\varphi_{21}\cdot\cos\psi_{34}\cdot\cos\theta_{43} - L\cdot\cos\varphi_{21}\cdot\sin\psi_{34}\cdot\sin\theta_{43} + K\cdot\cos\varphi_{21}\cdot\cos\psi_{32} + H\cdot\cos\varphi_{21} \\ L\cdot\sin\varphi_{21}\cdot\cos\theta_{43} + L\cdot\cos\psi_{34}\cdot\sin\theta_{43} \end{bmatrix} \qquad (5)$$

b) Velocity

Starting equation to determine velocity of the end point M is:

$$\bar{\mathbf{v}}_1^{M} = \mathbf{T}_{41} \cdot \mathbf{V}_{41_4} \cdot \bar{\mathbf{r}}_4^{M} , \qquad (6)$$

where $\mathbf{V}_{41}$ is velocity matrix of whole system. It determines as

$$\mathbf{V}_{41_4} = \mathbf{V}_{21_4} + \mathbf{V}_{32_4} + \mathbf{V}_{43_4} \qquad (7)$$

and matrixes $\mathbf{V}_{21}$, $\mathbf{V}_{32}$, $\mathbf{V}_{43}$ have meaning of velocity matrixes of neighbouring objects that are transformed to coordinate system of end term $O_1x_4y_4z_4$.

For the first determination the matrixes are following

$$\mathbf{V}_{21_2} = \begin{bmatrix} 0 & -\varphi'_{21} & 0 & 0 \\ \varphi'_{21} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \quad \mathbf{V}_{32_3} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & -\psi'_{32} & 0 \\ 0 & \psi'_{32} & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix},$$

$$\mathbf{V}_{43_4} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & -\vartheta'_{43} & 0 \\ 0 & \vartheta'_{43} & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}. \tag{8}$$

Transformation of velocity matrixes to the system of the end term are realized by scheme:

$$\mathbf{V}_{21_4} = \mathbf{T}_{43}^{-1} \cdot \mathbf{T}_{32}^{-1} \cdot \mathbf{V}_{21_2} \cdot \mathbf{T}_{32} \cdot \mathbf{T}_{43}, \tag{9}$$

$$\mathbf{V}_{32_4} = \mathbf{T}_{43}^{-1} \cdot \mathbf{V}_{32_3} \cdot \mathbf{T}_{43}. \tag{10}$$

Final velocity course of the point M to obtain by solving Eq. (7) and next (6)

$$\mathbf{v}_1^M = \begin{bmatrix} A \\ B \\ C \end{bmatrix}.$$

Where individual coordinate of velocity vector has shape:

$$A = \varphi'_{21} \cdot \cos\varphi_{21} \, (-L \cdot \cos\psi_{32} \cdot \cos\vartheta_{43} + L \cdot \sin\psi_{32} \cdot \sin\vartheta_{43} - K \cdot \cos\psi_{32} - H) +$$

$$+\psi'_{32} \cdot \sin\varphi_{21} \cdot (L \cdot \sin\psi_{32} \cdot \cos\vartheta_{43} + L \cdot \cos\psi_{32} \cdot \sin\vartheta_{43} + K \cdot \sin\psi_{32}) +$$

$$+\vartheta'_{43} \cdot \sin\varphi_{21} \cdot (L \cdot \cos\psi_{32} \cdot \sin\vartheta_{43} + L \cdot \sin\psi_{32} \cdot \cos\vartheta_{43}),$$

$$B = \varphi'_{21} \cdot \sin\varphi_{21} \cdot (-L \cdot \cos\psi_{32} \cdot \cos\vartheta_{43} + L \cdot \sin\psi_{32} \cdot \sin\vartheta_{43} - K \cdot \cos\psi_{32} - H) -$$

$$-\psi'_{32} \cdot \cos\varphi_{21} \cdot (L \cdot \sin\psi_{32} \cdot \cos\vartheta_{43} + L \cdot \cos\psi_{32} \cdot \sin\vartheta_{43} + K \cdot \sin\psi_{32}) -$$

$$-\vartheta'_{43} \cdot \cos\varphi_{21} \cdot (L \cdot \cos\psi_{32} \cdot \sin\vartheta_{43} + L \cdot \sin\psi_{32} \cdot \cos\vartheta_{43}),$$

$$C = \psi'_{32} \cdot (L \cdot cos\,\psi_{32} \cdot cos\,\vartheta_{43} - L \cdot sin\,\psi_{32} \cdot sin\,\vartheta_{43} + K \cdot cos\,\psi_{32}).$$

c) *Acceleration*

To determine total acceleration of the end point M have to solve equation:

$$\bar{\mathbf{a}}_1^{\mathrm{M}} = \mathbf{T}_{41} \cdot \boldsymbol{B}_{41_4} \cdot \overline{\boldsymbol{r}_4^{\mathrm{M}}}, \tag{11}$$

where $\boldsymbol{B}_{41}$ is matrix of total acceleration of the end point M of handling system. It obtains as a sum of square velocity matrix and matrix of incomplete acceleration of the whole system.

$$\boldsymbol{B}_{41_4} = \boldsymbol{V}_{41_4}^2 + \boldsymbol{A}_{41_4}. \tag{12}$$

An incomplete acceleration matrix obtains by solving equation:

$$\boldsymbol{A}_{41_4} = \boldsymbol{A}_{21_4} + \boldsymbol{A}_{32_4} + \boldsymbol{A}_{43_4} + \boldsymbol{A}_{\mathrm{RC}_4} \tag{13}$$

Acceleration solving is very heavy on space, thus we do not show it. Due to considered motion velocity up to 1 rad/s and chosen dimension of handling arms and too their weight the acceleration is possible ignore. It is simplification of the strength design and dimensioning of drive components.

3. Mechanical design of handling system

Since the beginning the total mechanical design of handling system was oriented to be realized by own means of department. Therefore, we oriented to design of separated component of system by basic methods of machining.

The entire structure of handling system is divided into two separate blocks. The module implements the first rotary unit, i.e. rotation of the manipulator, and the module, which consists of two pivoting arms. The rotary module is schematically shown in Fig. 4.

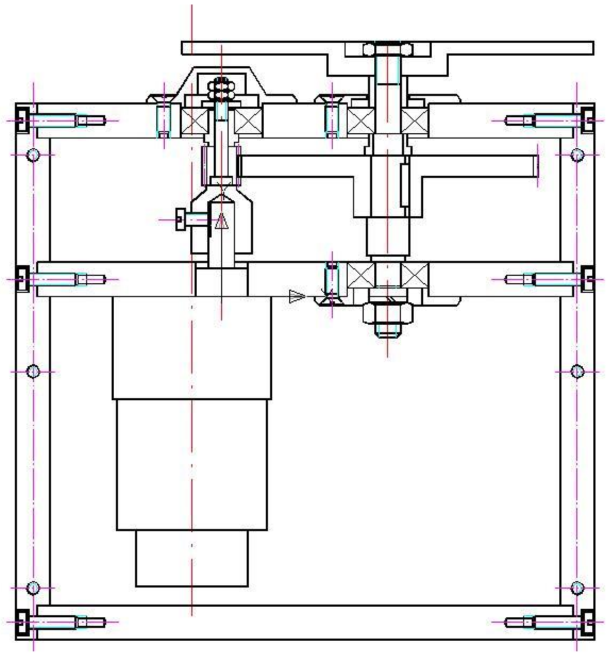

Fig. 4. The rotary module of handling system

The module is designed as a single-stage transmission. The engine rotation is transmitted to the output platform using one pair of gears with gear ratio i = 8.7. The driveshaft with a gear and with an output platform is mounted in ball bearings. The shaft of the pinion is an extension of the electric motor shaft and the free end is put in a ball bearing. The case of the rotation module is made from duralumin simple shape profiles. The connection is made via screws. The second element of arm is shown in Fig. 5.

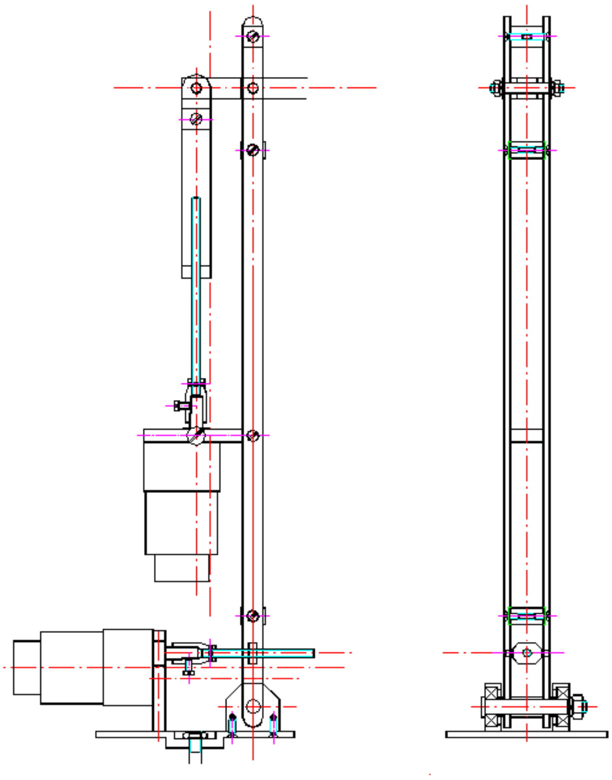

Fig. 5. Arms of handling system

The entire concept of arms design and locating of drivers is visible from Fig. 5. The arms were chosen with separate drive and there is not mechanical connection between them. Their controlling is individual. With regarding the length of arm the vertical arm is designed from sheets steel, horizontal arm is made from duralumin profile. The electric motors are put into mother board movably (pendular) so that it can adapt to changing position of the screw when arms turning. Transfer of motion from the engine to the arms was chosen using self-locking screws. Thus, the braking system may not be used that would have secured the position of the arms when the driving force drives is turn off. Thus the braking system may not be used, that secured the position of the arms when you turn off the driving force drives.

4. Drives of handling system

During specification phase of requirements for manipulation tasks that it should be fulfilled by the handling system is desirable that all moving units were in terms of management and control independent of each other. Each of the controlled axes thus must have its own propulsion. Another requirement was the usage of the same type of drive energy for engine as the drive and control of the whole chassis because of simpler power subsystem of the vehicle. Due to these requirements three identical electric engines were chosen. Manipulator is therefore equipped with three DC motors with additional mechanical gearbox.

The DC motors Pololu Metal Gearmotor* with a supply voltage of 12 V and a torque of 0.14 Nm were applied. The motors are equipped with a metal reduction gear with a gear ratio of 70 : 1 and encoder for sensing the position of 4480 pulses per revolution. All three parts form a compact element and their mechanical construction is shown in Fig. 4 and 5.

Two modules TReX Dual Motor Controller DMC01 manages trio of electric motors. Each module allows full control of two motors. Therefore one of the modules creates a reserve for operating another motor for just now unspecified extension. Due to usage of two control modules it is necessary to implementation expanded protocol based on serial communication, see Fig. 6.

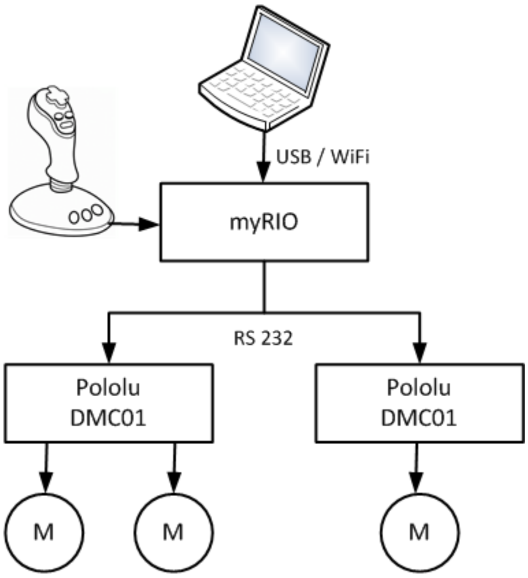

Fig. 6. Connection of trio of motors to controller

The interface between the user and handling system is provided by the control board myRIO produced by National Instruments. The device allows direct control of all three axes of manipulator by joystick respectively by another control hardware. Or it can be used PC to control the motors via USB cable or WiFi connection.

* 70:1 Metal Gearmotor 37Dx52L mm with 64 CPR Encoder

5. Conclusion

The considered designed handling system of mobile robot is an early stage of development. In essence, this is the first prototype that was designed in the context of solving a scientific task. It designed to test the theoretically selected variables of construction as well as drive and control. At this stage of development other issues are not solved. E.g. putting of a control unit, a power supply wiring, distribution of a control cables, drives and bearings protection from the weather, the treatment of the extreme positions stops and limit switches, etc. We can say that dimensions of individual handling arms, weight of almost all part and shape will be modify. Most of these tasks will be solved in the next step of development.

Acknowledgements

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