Dynamic model of a robotic platform with 6 degrees of freedom

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Abstract. The paper presents the study of kinematic and dynamic characteristics of the robotic mobility platform (RMP) to determine inertia-force parameters depending on the nature of the implemented motion path. The method is implemented on the basis of parameterized digital simulation models with parallel kinematics, which allow determining acceleration and force response in the joints of structural components at given geometric parameters of the platform design.

1. Introduction

Modern technical industries quite often consider the use of mechanisms using parallel kinematics. First of all, these are robots with kinematic chains in a parallel scheme. Such mechanisms can have a number of advantages: high speed and acceleration, rigidity, payload [1, 2, 3].

The prospects of such mechanisms are determined by a wide range of possibilities that solve a variety of technical problems. Thus, RMP built on the basis of mechanisms with parallel kinematics can provide the following types of operational tasks: tests of high-tech equipment and its individual components; use as mobile bases in simulators for equipment control (cars, aircraft, specialized equipment); creation of specialized units that hold various devices and actuators in a given position during movement. The use of parallel mechanisms is quite effectively implemented in some simulators that simulate the processes of mobile hardware control, where 6-power positioning systems (Stewart platform, Hexapod) are implemented as the main driving mechanisms [4].

As a rule, the design of energy-efficient mechanisms with parallel kinematics requires additional study to determine their design characteristics in order to provide the given parameters of its working space [5, 6, 7], to define optimal trajectories, as well as dynamic and inertial characteristics [8, 9, 10].

One of the important and relevant issues is the study of the power characteristics arising in the support and joint elements of mobile systems depending on a developed path.

2. RMP dynamic model

The object of the study is a 6DOF robotic mobility platform. The platform represents a compact six-axis structure (Fig. 1) with 6 degrees of freedom and designed for the maximum operation speed. The structure of the platform includes the following main components: base 1, movable platform 2, electric cylinders (EC) 3, joints 4. Table 1 shows technical characteristics and kinematic parameters of the platform.
Figure 1. Design of 6DOF robotic mobility platform. Main mechanical components: 1 – base; 2 – movable platform; 3 – electric cylinder, 4 – joints.

| Parameter       | Units | Value |
|-----------------|-------|-------|
| Width           | mm    | 1855  |
| Length          | mm    | 1654  |
| Height          | mm    | 1385  |
| Weight          | kg    | 550   |
| EC rod stroke   | mm    | 200   |
| Payload         | kg    | 987   |

Table 1. Technical characteristics of the robotic mobility platform.

Table 2. RMP kinematic parameters

| Parameter         | Value, mm | Speed, mm/s | Acceleration, mm/s² |
|-------------------|-----------|-------------|---------------------|
| Longitudinal travel | -110 .. +120 | 6.6         | 6.5                 |
| Lateral travel    | -110 .. +110 | 6.6         | 6.5                 |
| Vertical travel   | -110 .. +110 | 6.6         | 6.5                 |

A virtual prototype of a robotic platform was developed to simulate kinematic and dynamic parameters characterizing the operating conditions under workloads (Fig. 2). The digital layout with the properties of a parameterized simulation model was created in the MSC Adams software complex, which consists of 4 main idealized elements (parts): base, movable platform, rod, piston. These elements are in full conformity with the geometrical and functional parameters given in Tables 1 and 2 of the considered RMP design.
Figure 2. Digital simulation model of RMP made in MSC Adams: M1...M6 – markers of corresponding joints; H_U – upper spherical joint; H_D – lower spherical joint; CJ – cylindrical joint; CG – center of mass; P – payload at the center of mass.

The following special software operators of the Adams application are used to simulate real structural interfaces of the RMP: support (Down) is fixed on the Ground using a Fixed Joint. At points where the pistons are attached to the base (H_D) they are connected via a Spherical Joint. Similarly, EC rods are coupled to a platform working surface (H_U). To simulate the movement of the electric cylinder, the piston and the rod are connected to each other at contact points (CJ) by a Cylindrical Joint. The external forces are given as gravity G directed vertically downward (in the direction of the axis – OY) and the payload P applied at the point of the center of mass, which is set in accordance with the requirements of the designed RMP industrial model.

As a simulation of the RMP movement, translational movements were created in 6 cylindrical joints using the Translation Joint Motion software operator, which implements the established laws of linear movement in the MSC Adams application. The time-dependent movement is defined using a special STEP function. The STEP function approximates an ideal mathematical piecewise-defined function, but without breaks. The syntax of the STEP function: STEP (q, q1, f1, q2, f2), where: q – independent variable; q1 – initial value for q; f1 – initial value for f; q2 – final value for q; f2 – final value for f.

For the developed model, the law of motion of the electric cylinder will be as follows:

\[
step(time, t_0, l_0, t_n, l_n) \cdot l + step(time, t_n, l_k, t_m, l_p) \cdot l + \cdots,
\]

where time – independent variable (time); t_0 – initial time value for 1 section; t_n – final time value for the 1st section and initial time value for the 2nd section; t_m – final time value for the 2nd section; l_0, l_k, l_p – initial and final values of movement of the electric cylinder rod, \(-1 \geq l_0, l_k, l_p \leq 1\); l – maximum value of movement of the electric cylinder rod.

3. RMP paths

Three types of trajectories (paths) were considered for the study. The path types are selected to implement the most stringent operating conditions in terms of the resulting power loads in structural elements, as well as to determine the capabilities of the model to arrange different combinations of paths. All paths were tested at the maximum speed that the RMP mobile part. The geometric representation of paths is given in Fig. 3. The initial position for all types of paths is the position at which the movable part of the platform is in a horizontal position, the geometric centers of the base and the movable part are on the same vertical line (Y axis in the model), the zero initial position in height is selected with the possibility of moving in two directions vertically – down or up to the same value equal to 110 mm.

Path 1 consists of 3 motion sections with primitive movements. In each section, the initial position first moves to a maximum value in the direction of the corresponding coordinate axis or rotates relative...
to the corresponding axis, then to a maximum value in the opposite direction and at the end returns to the initial position. Accordingly, the following components are tested sequentially for the first path: 1) movement of the RMP working surface along the Y axis parallel to the base; 2) movement along the Z axis parallel to the base; 3) turn about the OY axis passing through the center of mass and return to the initial position.

Path 2 can also be divided into 3 sections: 1) from the initial position, the inclination angle of marker 4 changes to the minimum value (-9°), and markers 5 and 6 raise to the maximum value; 2) marker 4 changes the inclination angle to the maximum (+9°), marker 5 reduces the inclination angle to the minimum (-9°); 3) return to normal position.

The principle of path 3 is as follows. From the position when all electric cylinders are compressed (movable part is moved down by -110 mm relative to the initial position), the movable platform is driven alternately by each EC. EC connecting markers 3 and 6 moves first, then, in t=6sec the EC connecting markers 2 and 6 begins to move, and further all ECs are sequentially switched on. After EC reaches the maximum value of rod movement, EC reverses the direction. Thereafter, the moving part of the RMP repeats the movement and stops in the uppermost position when the working surface is parallel to the base.

Figure 3. Motion paths of the RMP movable part: a – path 1; b – path 2; c – path 3.

4. Research results
Fixation and digital processing of dynamic characteristics were carried out during the studies using a digital model of a robotic mobility platform for each of the considered types of paths. The results of dynamic simulation are presented by accelerated curve of the center of mass and force values (reactions) in joints, which occur during the movement of a movable part of the platform in accordance with the specified path.

The graphs of variance, acceleration, as well as power characteristics (reactions in joint supports) are drawn for each corresponding path type. The following designations are introduced in the graphs below for the convenience of their analysis: H1T1, H1T2, H1T3 – graph headings for paths 1, 2 and 3.
respectively; ACM_M – curve (trend) of acceleration variation; M1FM, M2FM, M3FM, M4FM, M5FM, M6FM – curves (trends) of variation of force values in joints of supports M1, M2, M3, M4, M5, and M6, respectively.

Fig. 4 shows the acceleration graphs for the first type of path. The graph analysis shows the presence of peak acceleration values, the maximum of which occurs for the third part of the path (sections 3.1, 3.2, 3.3).

Figure 4. Variation of the center of mass acceleration for path 1.
Figure 5. Variation of the force values (reactions) in the supports for path 1.

Fig. 5 shows graphs of forces change in supports when studying the dynamics for path 1. The maximum values of force fall on the support joint (3). In this case according to section 2 of path 1 the movable platform performs a linear reciprocating movement in a direction parallel to the horizontal plane. The peak values of forces applied to joints occur when movable platform is maximally removed from the initial position and starts moving to the initial position.

The analysis of dynamic characteristics for path 2 is interpreted by the graphs shown in Fig. 6 and 7. The numbers 1, 2 and 3 in the graph field indicate individual path sections. Vertical lines represent the time boundaries of these sections.

Fig. 6 shows the acceleration graph of the RMP center of mass. Peak acceleration values occur in section 1 when the movable platform starts moving from the initial position to the lowest position.

The maximum values of force fall on the support joint M2 according to section 2 of path 2. In this case, the movable platform performs an inclined movement – lowering the marker M5.

Figure 6. Variation of the acceleration of the center of mass for path 2.
Fig. 7. Variation of force values (reactions) in supports for path 2.

Fig. 8. Position of platform at maximum reaction value in support marker 2.

Fig. 8 shows the spatial position of the RMP at time $t=75$sec when the largest resultant force is observed in the support marker 2. Markers 4 and 6 are in the highest position, and marker 5 is shifted to the base as much as possible.

The graphs on Fig. 9 and 10 show the changes in the acceleration of the center of mass and force parameters in support joints for path 3.

The analysis of force value variation shows peak values in lower support joints corresponding to the maximum displacement of the system center of mass to the corresponding joint. At the same time, the force values in lower joints are always larger than in the upper ones, as for all types of paths. The peak values for joints M1 and M2 are in the antiphase due to uniform cyclicity of working displacements set in time in models that simulate the operation of electric cylinders.

Fig. 11 and 12 show the spatial position of the RMP at which the maximum values of the acting forces obtained as a result of the simulation of movements for path 3 appear in the corresponding support markers.
Figure 9. Variation of the acceleration of the center of mass for path 3.

Figure 10. Variation of the force values (reactions) in supports for path 3.

Figure 11. RMP position at the maximum value of the sum of forces applied to support marker 2.

Figure 12. RMP position at the maximum value of the sum of forces applied to support marker 1.

The maximum values of forces acting on the supports, and, therefore, the reaction values in these supports obtained through the simulation during the movement of all the considered types of paths are
presented in Table 3.

The given research materials show the possibility of obtaining power characteristics in various loaded elements of the considered system in dynamics at different versions of paths. This may be necessary both at the design stage of a considered sample and when studying the reliability of the structure during operation. The dynamic RMP model developed in the MSC Adams system also allows modeling the movements of the center of mass, obtaining spatial motion paths of any point associated with model elements, their speed and acceleration.

Table 3. Peak values of power reactions in joints.

| Force parameter, N | Joint | M1 | M2 | M3 | M4 | M5 | M6 |
|--------------------|-------|----|----|----|----|----|----|
| Path 1             |       |    |    |    |    |    |    |
| X                  | -1541 | 1541 | 12 | 278 | -1461 | 1860 |
| Y                  | -5273 | -5273 | -6233 | 4508 | 4231 | 4231 |
| Z                  | -812 | -812 | 1624 | -1724 | 904 | 904 |
| mag                | 5486 | 5486 | 6397 | 4827 | 4653 | 4653 |
| Path 2             |       |    |    |    |    |    |    |
| X                  | -1502 | 1558 | 261 | -204 | -1650 | 1457 |
| Y                  | -4935 | -5089 | -5255 | 4647 | 4300 | 4300 |
| Z                  | -1161 | -1125 | 1835 | -2076 | 989 | 1201 |
| mag                | 5171 | 5440 | 5462 | 4782 | 4527 | 4527 |
| Path 3             |       |    |    |    |    |    |    |
| X                  | -1795 | 1795 | 428 | 712 | -1656 | 1656 |
| Y                  | -5593 | -5593 | -5157 | 4576 | 4395 | 4396 |
| Z                  | -892 | -892 | 1725 | -1721 | 944 | 944 |
| mag                | 5913 | 5913 | 5581 | 4779 | 4649 | 4649 |

5. Conclusion

The developed dynamic model may serve as a prototype of a digital twin in solving design and research problems to obtain the required technical characteristics of industrial samples of robotic mobility platforms taking into account their technological purpose.

One direction may be to obtain the necessary characteristics of actuating driving mechanisms, such as, for example, electric cylinders, for the required geometric parameters of movements and dynamic characteristics, which are given as initial data, as well as to make decisions on the design of bearing and supporting elements of the mechanical part.

On the other hand, by controlling the actuating driving mechanisms using the presented digital model of the RMP the obtained motion paths of the center of mass can be used to analyze the accuracy of motion control programs for their subsequent implementation in various simulators, including those used in training.

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