Movement simulation of flexible working body links in the Unity cross-platform development environment

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Abstract. The analytical modeling of multi-link mechanisms with a large number of degrees of freedom is a difficult task, therefore, it is advisable to use a simulation model. Since it is planned to use a flexible working body on an area overgrown with vegetation, this will require a significant number of elements and, as a result, it will be very difficult to perform work using computer-aided design. In this paper, a simulation model of a flexible working body is implemented in a cross-platform Unity development environment. In computer-aided design systems, we are limited to tools and algorithms created by developers. In Unity, we have the opportunity to create our own tools and algorithms, adding it to the links of interest to us, which are solids in the field of gravitational forces. We created a 3D model of each link of a flexible working body, connected it with hinges with the possibility of moving relative to each other. Added scripts to accelerate the rotor and save the coordinates of the links. Based on the obtained coordinates, dependencies were constructed to determine the kinematics of the links of the flexible working body, taking into account its bending in the vertical and horizontal plane under the action of gravity.

1. Introduction

One of the necessary operations for the care of forest crops is the removal of shrubs that interfere with their development. To remove shrubs, it is necessary to use mechanized means. One of the working bodies of such mechanized means is a rotor with chains. Each link of the chain has six degrees of freedom, therefore, to justify the parameters of the working body, it is necessary to use modern methods of mathematical modeling. A flexible working body in the form of a cable or chain can theoretically be represented as a system of material points that can move relative to each other in three planes, which reduces this task to the problem of rotating bodies relative to its centers of mass. A great contribution to the development of the mechanics of systems of material points and solids was made by Vilke V.G. [1,2]. In the works of Hui Ma, a model of a rotor with blades that takes into account lateral and torsional shaft deformations was studied [3]. A shaft and a hard disk are described by multiple points of concentrated mass connected by massless springs. The blade is represented as a single solid, while we need to consider a system of flexible body. The work of Chen Yong [4] is devoted to the study of the kinematics of rotating links with the help of virtual prototyping. In it, the paths of movement of the milling head are obtained using the Motion SolidWorks module; the range of its rotation is determined. In the work [5] a finite element model of a rotor taking into account the inertia of shaft rotation is presented. An equation of the rotor system is obtained, taking into account the damping of its mountings, and the vibration frequencies are determined. In our previous work, we
examined the analytical and simulation model of a flexible working body, performed in a computer-aided design system [6]. The dependences of the change in the coordinates of the centers of gravity of the links on time were obtained. The dependencies of the analytical and simulation models have sufficient convergence and are confirmed by laboratory studies. However, to study the process of cutting branches of a bush, it is necessary to create a simulation model capable of calculating a significant number of objects, so we decided to use the Unity cross-platform development environment to implement this approach.

2. Material and methods

The installation consists of a rotor 1 and links 3 connected by hinges 2 forming a flexible connection. The rotor is located in coordinate system 4 (figure 1). We take XOZ as the horizontal plane, and direct gravity down the OY axis. Flexible working bodies are located symmetrically, its initial position corresponds to free overhang under the influence of gravity. During rotation, kinetic energy is accumulated in flexible working bodies, it occupies a radial position. The change in rotor speed is shown in figure 2.

![Figure 1. Rotor with flexible working bodies.](image)

![Figure 2. Characteristics of the rotor acceleration.](image)

The orientation of the links and hinges with respect to the world coordinate system is repeated for all links, as an example in figure 3, the first hinge and link are considered. The given local coordinate systems are rotated relative to each other for a visual demonstration of the quaternion.

Links and hinges are presented in the form of solid bodies (Rigid body). The mass of two flexible working bodies is 1 kg, the rotor mass is 5 kg. We take the air resistance to the movement of objects equal to zero. The gravity acts on each link and hinge.
A hinge connects the rotor to the first link and then the hinges are between the links. Each hinge has six degrees of freedom (three translational and rotational). If necessary, you can set the limits of rotation angles (for the problem under consideration, no restrictions are required). To set the connection between the joints of the hinge, a spring interaction is established, described by the force required to change the position and the damping parameter.

![Diagram](image)

**Figure 3.** World and local coordinate system of the considered links: the coordinate system of the hinge Kpara-1 (a), the coordinate system of the link Zveno-1 (b).

The initial coordinates of the local coordinate systems of links and hinges are given in Table 1.

**Table 1.** Initial coordinates and rotation angles of links and hinges.

| Item name  | Position, m | Rotation, ° |
|------------|-------------|-------------|
|            | $X$ | $Y$ | $Z$ | $X$ | $Y$ | $Z$ |
| Rotor      | 0  | 0.01 | 0  | 0  | 0  | 0  |
| Zveno-1    | -0.164 | -0.055 | 0  | -90 | 0  | 90 |
| Kpara-1    | -0.164 | 0  | 0  | 0  | 0  | 0  |
| Zveno-2    | -0.164 | -0.135 | 0  | -90 | 0  | 90 |
| Kpara-2    | -0.164 | -0.07 | 0  | 0  | 0  | 0  |
| Zveno-3    | -0.164 | -0.215 | 0  | -90 | 0  | 90 |
| Kpara-3    | -0.164 | -0.15 | 0  | 0  | 0  | 0  |
| Zveno-4    | -0.164 | -0.295 | 0  | -90 | 0  | 90 |
| Kpara-4    | -0.164 | -0.23 | 0  | 0  | 0  | 0  |
| Zveno-5    | 0.164 | -0.055 | 0  | -90 | 0  | 90 |
| Kpara-5    | 0.164 | 0  | 0  | 0  | 0  | 0  |
| Zveno-6    | 0.164 | -0.135 | 0  | -90 | 0  | 90 |
| Kpara-6    | 0.164 | -0.07 | 0  | 0  | 0  | 0  |
| Zveno-7    | 0.164 | -0.215 | 0  | -90 | 0  | 90 |
| Kpara-7    | 0.164 | -0.15 | 0  | 0  | 0  | 0  |
| Zveno-8    | 0.164 | -0.295 | 0  | -90 | 0  | 90 |
| Kpara-8    | 0.164 | -0.23 | 0  | 0  | 0  | 0  |
In Unity, objects are rotated through quaternions, but Euler angles are presented in the interface for simplification (figure 4).

![Figure 4. Unity interface for displaying coordinates, rotation angles and scale.](image)

In Unity, links are moved using the matrix:

\[
\begin{bmatrix}
Q_x \\
Q_y \\
Q_z \\
1
\end{bmatrix} =
\begin{bmatrix}
P_x \\
P_y \\
P_z \\
1
\end{bmatrix} +
\begin{bmatrix}
v_x \\
v_y \\
v_z \\
0
\end{bmatrix}
\]

(1)

Where \( Q_x, Q_y, Q_z \) - coordinates of objects in the final position, \( m; P_x, P_y, P_z \) – coordinates of objects in the initial position, \( m; v_x, v_y, v_z \) – vector transferring an object from initial to final position, \( m \).

The rotation is performed using the matrix:

\[
\begin{bmatrix}
Q_x \\
Q_y \\
Q_z \\
1
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & 0 & 0 & \cos(\alpha) & 0 & \sin(\alpha) & 0 & \cos(\beta) & -\sin(\beta) & 0 & 0 \\
0 & \cos(\theta) & -\sin(\theta) & 0 & 0 & 1 & 0 & 0 & \sin(\beta) & \cos(\beta) & 0 & 0 \\
0 & \sin(\theta) & \cos(\theta) & 0 & -\sin(\alpha) & 0 & \cos(\alpha) & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1
\end{bmatrix}
\]

(2)

Where \( \theta, \alpha, \beta \) - rotation angles around the axes OX, OY, OZ, respectively, °.

In order to set the rotation of the rotor, add the script Sc1 increasing the angle along the OY axis. With each call, we increase the time until it reaches the limit value and pass it to the second value in the vector. A fragment of the script and its attachment to the link in the Unity inspector (figure 5).

```csharp
void FixedUpdate()
{
    timeI = timeI + 1;
    if (timeI > 400) timeI = 401;
    transform.Rotate(new Vector3(0, 1 * timeI, 0) * Time.deltaTime);
}
```

![Figure 5. Adding an acceleration script to the rotor.](image)

During the simulation of movement, we are able to save the kinematic parameters of objects of interest to us.
void Update()
{
    FileStream file = new FileStream(@"d:\1_13_x.txt", FileMode.Append);
    StreamWriter stream = new StreamWriter(file);
    stream.WriteLine(transform.localPosition.x);
    stream.Close();  file.Close();
}

Figure 6. Adding a script to the rotor to record the X coordinate.

To do this, add a script in the Unity inspector. S_1_13 to link 4, a fragment of the script and the inspector is shown in figure 6.

3. Results and discussion
Based on a simulation experiment in Unity, we obtained dependencies characterizing the displacement of the center of mass of the fourth link. As can be seen from the graphs in the first seconds, the coordinates of the center of mass are in the initial position, and in subsequent ones, an oscillatory movement is observed. The difference in the nature of the movement in the first and subsequent seconds is associated with the lifting of the flexible working body up and spring-damping ties specified in the simulation model (figure 7).

Figure 7. X, Y coordinate change for the fourth link calculated using a simulation model in Unity.

While calculating the analytical model, constant angular velocities were set and there was no movement of the working body in the vertical plane, so the graphs have a constant amplitude (figure 8) [6].
Figure 8. Changing the X and Y coordinates of the center of gravity of the fourth chain link based on an analytical mathematical model.

Based on the simulation model, we obtained changes in the vertical coordinate of the center of gravity of the fourth link (figure 9). In accordance with table 1, at the initial moment it is located at a distance of $-0.295$ m from zero, therefore, during acceleration, the vertical components have a positive value.

Figure 9. Changes in the Z coordinate of the fourth link based on the Unity simulation model.

Changing the position of the vertical coordinate of a flexible working body is consistent with the results obtained previously in a simulation experiment using a computer-aided design system [6].

4. Conclusion

Based on the obtained simulation model, the trajectories of the flexible inertial-chopping working body were calculated. The trajectories correspond to the results obtained earlier on the basis of an analytical mathematical model and a simulation model performed in a computer-aided design system.

The resulting simulation model allows designers of machines for mechanized removal of shrubs to evaluate the effect of acceleration of the rotor and circuit parameters on its functionality. So, you can determine how long it takes the rotor chains to reach a steady state operation. When cutting the bush, the inertia accumulated in the chain will be spent on the cutting process, which means that the working width will decrease. Thus, the efficiency of the machine will depend on the selection of rotor parameters. If you increase the inertia of the chain by increasing its length, then when accelerating, the chain links will hit each other, which will lead to rotor failure.
In contrast to the simulation models made in the computer-aided design system, the number of elements involved in the modeling process in Unity is much larger, which allows us to investigate the rotor operation in conditions close to real ones.

This approach allows you to build a hierarchy of models and use a flexible working body as an element of the model for the area on which vegetation to be removed grows.

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