The use of differentials to increase the efficiency of orienting robotic devices of agricultural equipment

Nickita Litiuga, and *Evgeniy* Podchasov*

Faculty of Robotics and Integrated Automation, Bauman Moscow State Technical University, Moscow, Russia

Abstract. Robots are used in modern agricultural equipment. There are several types of robot designs: articulated robots, delta robots, scara robots and others. Almost every robot has in its design an orienting device, designed to orient the tool, used by the robot in space. Orienting devices differ from each other by different structural diagrams of transmission mechanisms and types of links, functioning in the mechanisms. All orienting devices are united by a design feature, which consists in the fact, that in order to rotate the tool around the axis of any kinematic pair, which is the degree of mobility of the orienting device, it is necessary to rotate several electric drives. If you rotate with one electric drive, the tool will make a spherical movement. The reason for this effect is that the kinematic chains, through which rotation is transmitted from the electric drive to the tool, intersect with each other. The use of differentials in the design will allow the tool to rotate around one axis by one electric drive, which gives some advantages in motion control. The article describes the design features and the principle of operation of the orienting device with differentials.

1 Introduction

An industrial robot manipulator of medium load capacity usually has 6 degrees of mobility. Each degree of mobility is provided by a single-degree-of-freedom revolute kinematic pair. The movement of the links in the kinematic pair is ensured by servos that rotate the transfer mechanisms, the input and output links of which are connected to the i-th and i+1-th links of the manipulator, respectively [1].

Different types of transfer mechanisms are used in different manipulators (and within the same manipulator too): harmonic gearing, belt drives, planetary gearsets, etc. A six-degree-of-freedom manipulator has 6 kinematic pairs and 6 movable links. The first link in the kinematic chain is connected to a stationary frame, and the controlled tool or device operated by the manipulator is attached to the flange of the last – 6th link.

* Corresponding author: Podchasov@bmstu.ru

 https://doi.org/10.1051/bioconf/202410501029

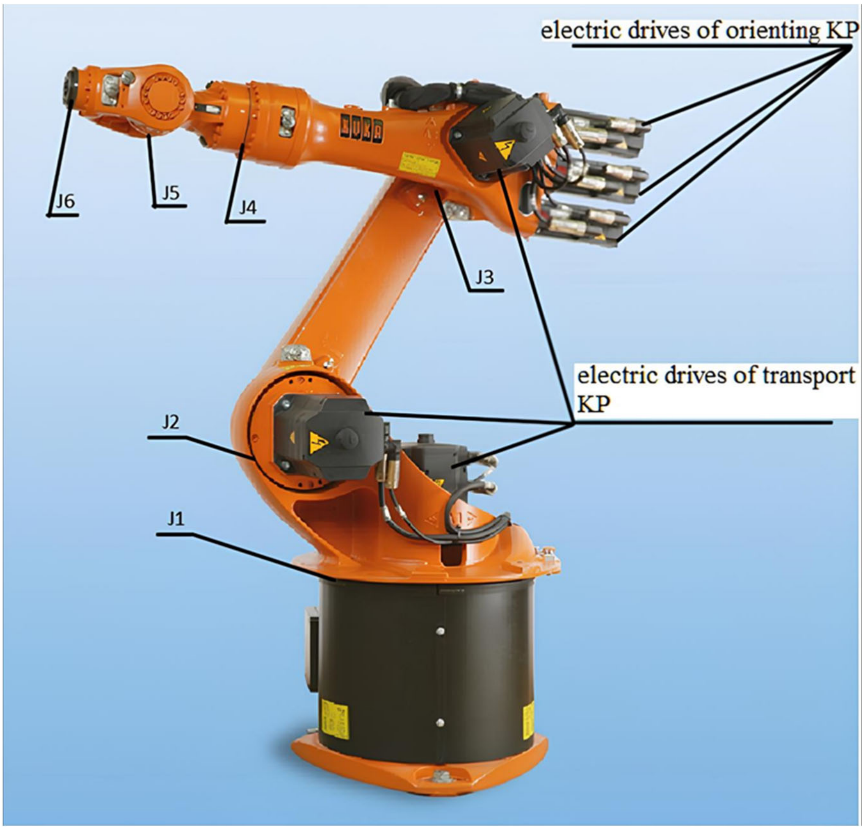

Fig. 1. Arrangement of electric drives and kinematic pairs.

Conventionally, kinematic pairs in the manipulator can be divided into transport and orienting pairs (Fig. 1, J1, J2, J3 – transport pairs, J4, J5, J6 – orienting pairs). Transport kinematic pairs are the first three kinematic pairs from the stationary frame, their main task is to ensure the transportation of the tool to the place of work. The electric drive of the transport kinematic pair is located near the kinematic pair, which it controls and its shaft is directly connected to the gearbox link. Orienting kinematic pairs are the last three kinematic pairs, their main task is to provide the desired angle of inclination and orientation of the tool in space near the place of work. Electric drives of the orienting kinematic pairs are located in one place, close to each other, at the beginning of the third link from the stationary frame and are connected to the corresponding kinematic pairs through drive shafts, this arrangement increases the load capacity of the manipulator (Fig.1).

2 The classical structure of the orienting mechanism

The most common design of the manipulator part responsible for the orientation of the tool has the following structure, shown in kinematic diagram (Fig. 2.) Transfer mechanisms of various types can usually be used, but in this kinematic diagram, a spur gears and a bevel gears are presented as transfer mechanisms.

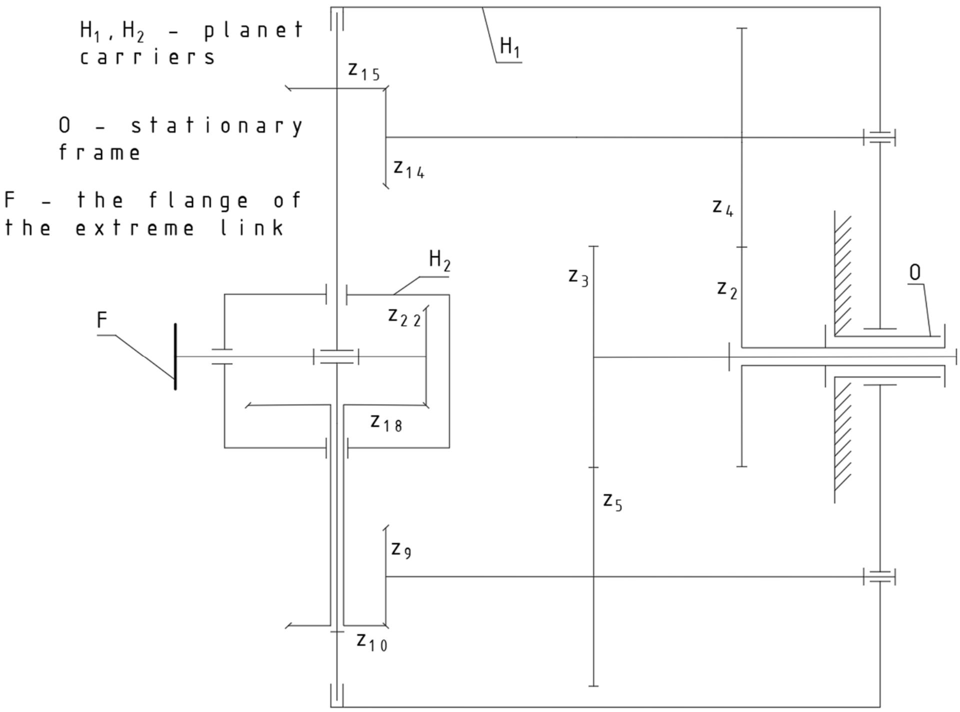

Fig. 2. The kinematic diagram of the most common design of the orienting device.

The kinematic diagram shows that in order to rotate the tool around one fixed axis (i. e. one KP, for example J6 in Fig.1), it is necessary to rotate several electric drives simultaneously and synchronously. When rotating only one electric drive, the tool will make a spherical movement. Such a control principle is a distinguishing feature of such a mechanism structure (Fig. 2). Different types of transfer mechanisms can be used, but if they are connected to a kinematic chain, the design of which is shown in Figure 2, then the principle of tool control will not change. For example, if you replace the Z15 and Z14 gears with a belt drive, this will not change the control principle. Changing the design in order to be able to control each axis of rotation of the manipulator by a separate electric drive can provide some advantages.

In this article, I consider the method of using the differential for the described task, as well as the advantages and disadvantages of such a design change.

3 The result of the application of analytical method for Investigation of the movement of links using differentials

In Figure 3 rotation around the nutation axis is determined by the angle θ, rotation around the axis of its own rotation is determined by the angle ϕ, rotation around the precession axis is determined by the angle ψ.

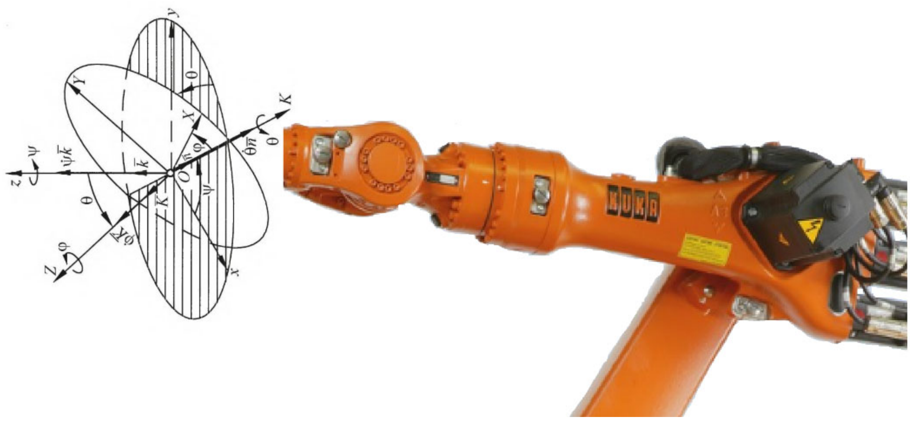

Fig. 3. Rotation of flange by angles of Euler.

Let's take a closer look at the kinematic diagram of the part of the manipulator responsible for the orientation of the tool (Fig. 4).

This design allows you to rotate the flange F of the output link of the kinematic chain around three axes: shaft axis 4 (rotation around the nutation axis), shaft axis 7 (rotation around the axis of its own rotation), fixed axis Z (rotation around the axis of precession).

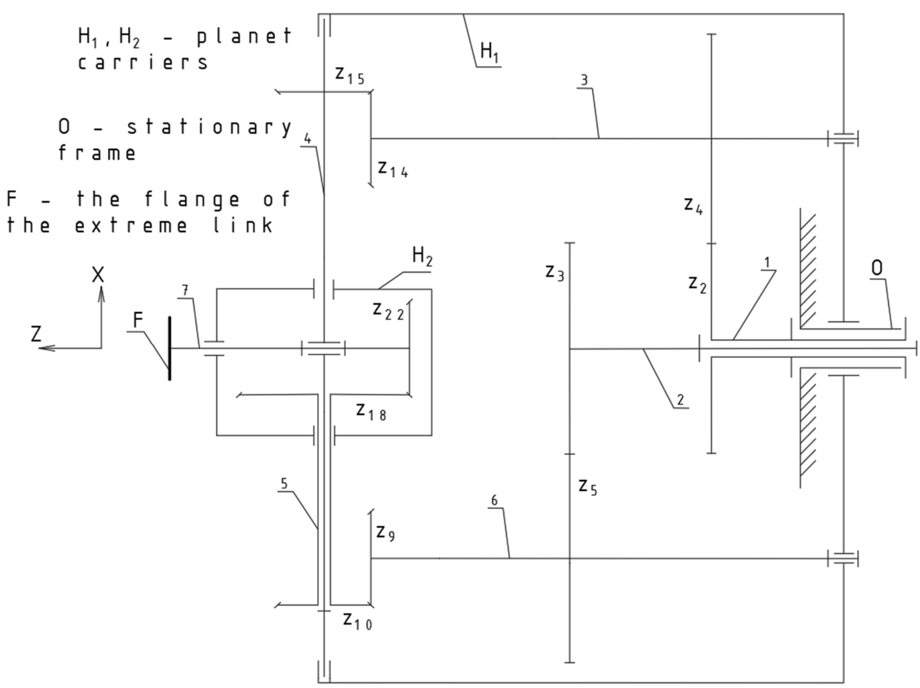

Fig. 4. The kinematic diagram of the most common design of the orienting device. (with coordinate axes).

Let's take a closer look at the kinematic diagram of the part of the manipulator responsible for the orientation of the tool (Fig. 4).

The output shafts of the electric drives are connected to shafts 1, 2 and carrier H1, respectively. By rotating the shaft 2, it is possible to rotate the flange F around the axis of the shaft 7 (rotation around the axis of its own rotation) through the gears Z3, Z5, shaft 6, gears Z9, Z10, shaft 5, gears Z18, Z22 (Fig.4). In order to rotate the flange F around the axis of the shaft 4, it is necessary to synchronously rotate the shafts 1 and 2, because when the gear Z18 (driven by the shaft 2) is stationary, the rotation of the shaft 4 (driven by the shaft 1 through the gears Z2, Z4, shaft 3, gears Z14, Z15,) will cause the flange F to rotate around the axis of the shaft 4 and therefore the rolling of the gear wheel Z22 on the gear wheel Z18, which, in addition to rotation around the axis of the shaft 4, there will also be rotation around the axis of the shaft 7. Thus, in order to rotate the flange F around the axis of the shaft 4, it is necessary to rotate the shaft 1 and by rotating the shaft 2, correct the rotation of the flange F around the axis of the shaft 7 due to rolling of the gear wheel Z22 on the gear wheel Z18. Similarly, in order to rotate the flange F around the fixed Z axis (rotation around the precession axis), it is necessary to rotate the carrier H1 and compensate by rotating the shafts 1 and 2 for rolling the gears Z4 and Z5 over the gears Z2 and Z3, respectively, thus eliminating rotation of the flange F around the shaft axis 7 and the shaft axis 4.

To control the rotations of the flange F around each of the three axes separately by each electric drive, you can change the design by including three differentials in it (Fig. 5).

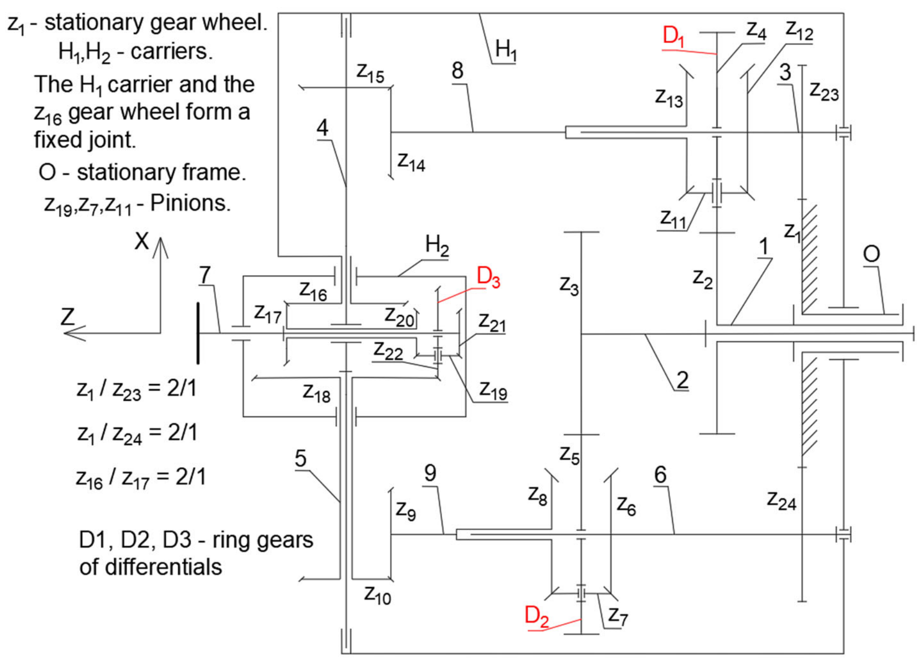

Fig. 5. The kinematic diagram of an orienting device with differentials.

A differential is a type of planetary gear that allows you to split the movement from one drive shaft into several shafts or combine the movement of several shafts into one drive shaft [2]. Differentials are most often found in the design of a car [3].

Let's take a closer look at the principle of operation and design of the D1 differential.

The D1 differential consists of a Z4 ring gear, a Z11 pinion, and Z12 and Z13 side gears.

When the carrier H1 is stationary, the gear wheel Z12 is stationary because it is fixed to the shaft 3, the rotation of which is fixed by the fixed gear wheel Z1 through meshing with Z23, therefore the differential works like a planetary gearset with W = 1 [4], transmitting rotation from shaft 1 through ring gear Z4, pinion Z11 (rolling on the stationary Z12) and side gear Z13.

The speed of rotation of the parts in the differential is described by the following expression:

$$\omega_1 - i \cdot \omega_2 = (1 - i) \cdot \omega_D \quad (1)$$

Where ω_1 and ω_2 – angular velocities of the side gears, ω_D – angular velocity of the ring gear, i – speed ratio between side gears with a fixed ring gear.

When the carrier H1 rotates at a speed of ω_H and the shaft 1 is stationary, the gear wheel Z23 will roll over the stationary gear wheel Z1, as well as the ring gear Z4 will roll over the stationary gear wheel Z2. Using the analytical method of research, we will find the speed of rotation of the shaft 3:

$$\frac{\omega_3 - \omega_H}{\omega_0 - \omega_H} = -\frac{Z_1}{Z_{23}} = -2 \quad (2)$$

Where ω_3 – angular velocity of the shaft 3, ω_0 – angular velocity of the stationary frame (i. e. $\omega_0 = 0$). We can find from equal (2):

$$\omega_3 = 3\omega_H \quad (3)$$

Using the analytical research method, we will find the rotation speed of the ring gear Z4:

$$\frac{\omega_{Z4} - \omega_H}{\omega_{Z1} - \omega_H} = -\frac{Z_1}{Z_4} = -1 \quad (4)$$

Where $\omega_{Z1} = 0$ (stationary) and from (4):

$$\omega_{Z4} = 2\omega_H \quad (5)$$

The speed ratio between the side gears of differential D1 with a fixed ring gear i = –1 (because Z12 = Z13). Let's put expressions (3) and (5) in (1):

$$\omega_{Z13} - (-1) \cdot 3\omega_H = (1 - (-1)) \cdot 2\omega_H \quad (6)$$

From this expression, it can be found that $\omega_{Z13}=\omega_H$, and therefore the shaft 8 (connected to Z13) rotates synchronously with the carrier H1 with equal speeds when the shaft 1 is stationary, i.e., relative to the carrier H1, the shaft 8 is stationary. As a result, when the carrier H1 rotates and the shaft 1 is stationary, the flange F rotates only around the stationary axis Z (rotation around the precession axis), there is no rotation around the axis of the shaft 4.

The differential D2 works in a similar way, separating the rotation of the carrier H1 and shaft 2, and the differential D3, separating the rotation of shaft 1 and shaft 2.

4 Conclusion

Thus, the differential D1 allows you to separate and make independent rotations of the flange F around the axis of the shaft 4 (rotation around the axis of nutation) and the stationary axis Z (rotation around the axis of precession), the differential D2 allows you to separate and make independent rotations of the flange F around the axis of the shaft 7 (rotation around the axis of its own rotation) and the fixed axis Z (rotation around the axis of precession), the differential D3 allows you to separate and make independent rotations of the flange F around the axis of the shaft 7 (rotation around the axis of its own rotation) and the axis of the shaft 4 (rotation around the axis of nutation).

The modified design has the following advantages.

The use of a modified design (with differentials) of the orienting device makes it possible to put individual electric drives on the brake during the movement of the manipulator, if it is not necessary to rotate the tool around the axis for which the corresponding electric drive is responsible. This allows you to turn off unused electric drives right in the course of movement of the manipulator, thereby saving electricity. There may be sections of the motion trajectory on which the output link of the manipulator moves with the rotation of one or two of the three orienting axes, and the output link is affected by a force that is balanced by torque from all three orienting axes. In such sections of the trajectory, using the described design of the orienting device (with differentials), it is possible to apply a brake to fix the axes that should not rotate in the required section of the trajectory, then the torque will be created not by electric drives, but by the brake. The electric drives of the fixed axes in this section can be switched off, thereby saving electricity. Such a control algorithm is impossible with the classical design of the orienting device (without differentials). For the productivity of robots in agro equipment, energy efficiency is more important than for robots in factories [5,6], since robots in the field run on batteries [7,8], but factories have power supply from the electric grid. It is possible to increase the accuracy because the error of the disconnected drives has no effect. When forming the law of motion of the rotation of the output link around a certain axis, it is no longer necessary to take into account the rotation of the output link around other axes, this allows you to reduce the number of mathematical operations when forming the law of motion.

The disadvantages will be that such a structure is much more difficult to assemble, it contains more parts and, therefore, costs more.

Modern agro equipment has a row of robotic devices used for digging, hoeing, weed eradication, extermination of insects and reclamation works [9]. The design of the orienting device proposed in this article can increase the energy efficiency of robotic devices, especially those that cultivate the land.

References

1. D. K. Muhamediyeva, M. Fozilova, E3S Web of Conf. **402**, 03050 (2023).
2. G. Ankinovich, A. Verzhbitski, A. Antonyan, IOP Conf. Ser.: Mater. Sci. Eng. **820**, 012025 (2020).
3. H. Zhang, Y Zuo, J. Zhang, H. Yang, S Chen, IOP Conf. Ser.: Earth Environ. Sci. **512**, 012162 (2020).
4. J. J. Uicker, G.R. Pennock, J.E. Shigley, *Theory of machines and mechanisms 6th edition*, 405-408, (2023).
5. E. Amirova, I. Safiullin, A. Sakhbieva, T. Aygumov, BIO Web Conf. **37**, 00014 (2021).
6. S. A. Afolalu, O. M. Ikumapayi, S. A. Ushe, S. O. Ongbali, A. Abdulkareem, M. E. Emetere, O. U. Iheanetu, E3S Web of Conf. **309**, 01002 (2021).
7. R. Baratov, A. Mustafoqulov, E3S Web of Conf**. 401**, 04006 (2023).
8. R. Filippov, D. Khort, E3S Web of Conf. **493**, 01003 (2024).
9. Y. Shvets, D. Morkovkin, M. Basova, A. Yashchenko, T.Petrusevich, E3S Web of Conf. **480**, 03024 (2024).