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PRIMARY CRITERIA FOR SELECTING GEARBOXES FOR AXES OF 6-AXIS INDUSTRIAL ROBOTS

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Abstract: *The choice of mechanical power transmissions is one of the key tasks in robotics engineering. Their characteristics largely affect the final performance of industrial robots. Since each axis has a specific function, each one of them needs a different gearbox. This paper analyses the main factors to be considered when selecting gearboxes for a 6-axis robot.*
Keywords: 6-axis industrial robots, high precision gearboxes, selection criteria

1. INTRODUCTION

The fourth industrial revolution brought about tectonic changes in large industrial systems, especially in electronic, automotive and metal processing systems, where robots perform various tasks such as material transport, machine servicing, welding, polishing, painting, assembly, control, packaging, sorting, palletizing... [1,2,3,4]. In order to perform most of these tasks, the robot needs to have six degrees of freedom, three for positioning and three for orientation of the end effector in space [5]. Since the rotational speed of the actuator is high compared to much slower mechanical rotation of the joints, it is necessary to significantly reduce the rotational speed and increase the torque. This is achieved using gearboxes, which greatly affect the final performance of industrial robots. According to available research data, gearboxes account for as much as 35% of the total robot costs, actuators account for 20%, and controllers only for 15% [6].
Since parts of a robot are in continuous motion, speeding up and slowing down, gearboxes in joints need to provide not only high rated torque and emergency stop torque but also high acceleration. In industrial robots, positioning accuracy and repeatability are very important. Positioning accuracy is the difference between the requested and the obtained position, while repeatability is the ability to achieve the same requested position over and over again. Although these two characteristics are interrelated, repeatability differs from accuracy and is usually much more important. In order to achieve a repeatability of ± 0.02 mm for an industrial robot with a reach of up to 700 mm, the robot needs to have an angular repeatability of only ± 5.9 $arcsec$ in the base axis [7]. In order to achieve this level of repeatability without the use of expensive high resolution encoders, it is necessary to use zero backlash gearboxes and not the conventional ones. Another major disadvantage of conventional gearboxes is the limitation of the gear ratio in single-stage gearboxes. In order to have an optimal reduction in rotational speed and increase in torque, i.e. to achieve the reduction ratio of 1:171 or 1:220, as needed in the joints of some industrial robots [8], it is necessary to install multi-stage gearboxes. Furthermore, one should not leave out low efficiency of conventional gearboxes, which has a negative impact on energy efficiency [9].

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At present, only high precision reducers can meet all the requirements including high accuracy and repeatability, zero backlash, high torsional rigidity, a combination of high torque and low weight (torque density), high efficiency and high gear ratios without taking up much space. The most widely used high precision reducers are rotate vector (RV) reducers, which are based on cycloid gears, and harmonic reducers [10,11]. Both reducers have high gear ratios, but since RV reducers have a higher load capacity they are usually installed in more loaded joints (base, shoulder, elbow). Harmonic reducers are compact and simple in structure hence they are usually installed in less loaded joints (forearm, hand). At the moment, RV reducers make up 60% and harmonic only 15% of all the reducers used in industrial robots [6]. This paper analyses the main factors to be considered when selecting gearboxes for axes of industrial robots.

2. REQUIREMENTS IN SPECIFIC AXES

In industrial robots, each joint can rotate in a specific axis (Figure 1). Generally, in a 6-axis robot, axis 1 allows the robot to move its arm to the left or right, axis 2 (shoulder) provides the ability to move the upper arm back and forth, axis 3 (elbow) allows the forearm to be raised and lowered, axis 4 allows the rotation of the forearm, axis 5 (wrist) enables the raising and lowering of the hand, axis 6 enables the rotation of the hand [12]. Since each axis has a specific function, each one requires a special gearbox.

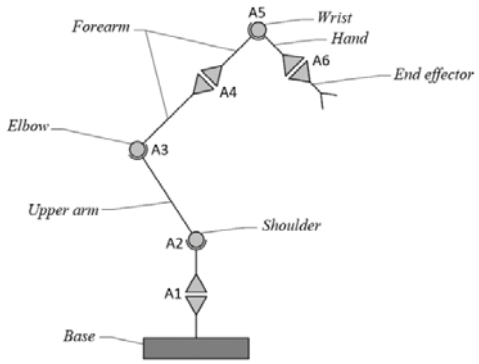


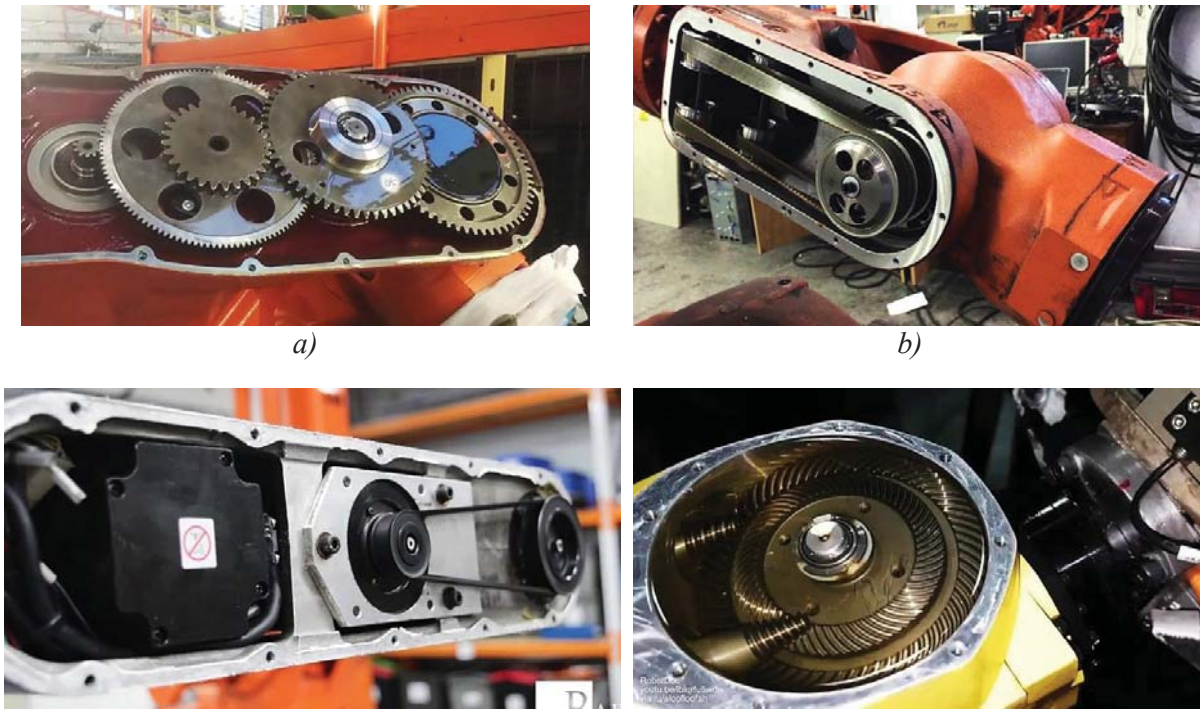
Figure 1. Kinematic structure of a 6-axis robot

When a load is applied to the end effector of a 6-axis industrial robot, the largest moments occur in the first joints. Due to the large lever arms, the rotation of the first joints have the greatest effect on the end effector positioning errors [13]. Therefore, gearboxes in axis 1 must have solid and robust construction in order to provide the necessary stability at high tilting and bending moments. In order to enable internal routing of power and data cables, as well as of supply hoses for painting or welding robots, it is necessary to use hollow shaft gearboxes.

Since axes 2 and 3 are also subjected to large loads when the robot moves, especially axis 2 which carries 70-75% of the total robot weight [14], their gearboxes need to provide high torques and have high torsional rigidity. Here, the cables and hoses are not routed internally but externally, so hollow shafts are not necessary. Since actuator weights also have negative effects on the load of axes 2 and 3, they are very rarely placed directly next to the gearboxes for axes 4, 5 and 6. For these three axes, they are mounted externally in the direction of axis 4. As a result, there is a need for intermediate transmission systems whose main role is to transfer the torque from the actuators to the remote gearboxes [15]. To date, several different construction solutions have been implemented. They are shown in Figure 2 [16]:

- In *IRB 6620* robots with a payload capacity of up to 150 kg in axis 5 - raising and lowering the hand, *ABB* uses cylindrical gear pairs which provide higher torque but much lower precision (Figure 2.*a*).
- In *KUKA KR5* robots with a payload capacity of up to 5 kg, the actuators and the gearboxes in axes 5 and 6 are connected by toothed timing belts (Figure 2.b).

- In *Yaskawa Motoman MA1400* robots with a payload capacity up to 3 kg, the actuator and the gearboxes are also connected by toothed timing belts, but here the actuators are not too far away from their gearboxes (Figure 2.*c*).
- *FANUC* uses special hypoid gears with a payload capacity of up to 12 kg in *M-10iA* robots (Figure 2.*d*).



a) *b)* *c)* *d)*

Figure 2. Intermediate transmissions from the actuator to the joint gearbox in axes 5 and 6: a) *ABB*; b) *KUKA*; c) *Yaskawa Motoman*; d) *FANUC*

In general, for rotation of the forearm (axis 4), it is necessary to use gearboxes with high torsional rigidity and slightly lower torques. They often need to have hollow shafs to allow installation cables to be passed through the gearbox. For axes 5 and 6, more compact and lightweight gearboxes with solid shafts are used, although in axis 6, it is sometimes necessary to use a hollow shaft, depending on the actuator in the end effector [17].
All these requirements for gearboxes in robot axes are summed up in Figure 3.

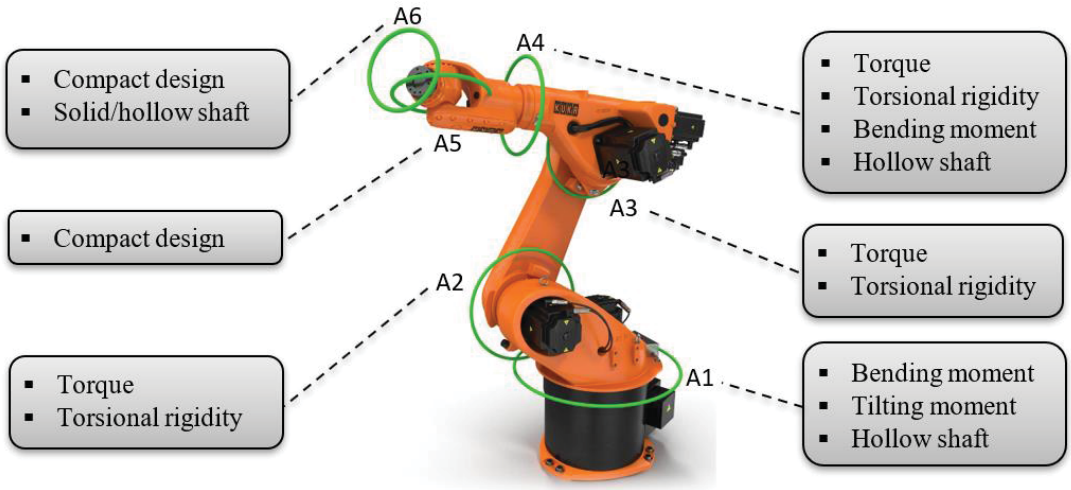


Figure 3. Gearbox requirements for axes of industrial robots *KUKA KR 60-3*

3. A COMPARATIVE ANALYSIS OF CHARASTERISTICS IN SPECFIC AXES

A comparative analysis of the characteristics of a 6-axis industrial robot axes with a payload of up to 150 kg is shown in Figure 4 [17]. Other important robot characteristics include the loss of hysteresis/lost motion below 1 $arcmin$, speed and acceleration above 100 $°/sec^2$, positioning accuracy and repeatability less than 20 $arcsec$. The trend lines are formed based on the mean values of the quantities. It can be seen that the highest torques are required in axes 2 and 3, while the highest torsional rigidity is needed in axis 4.

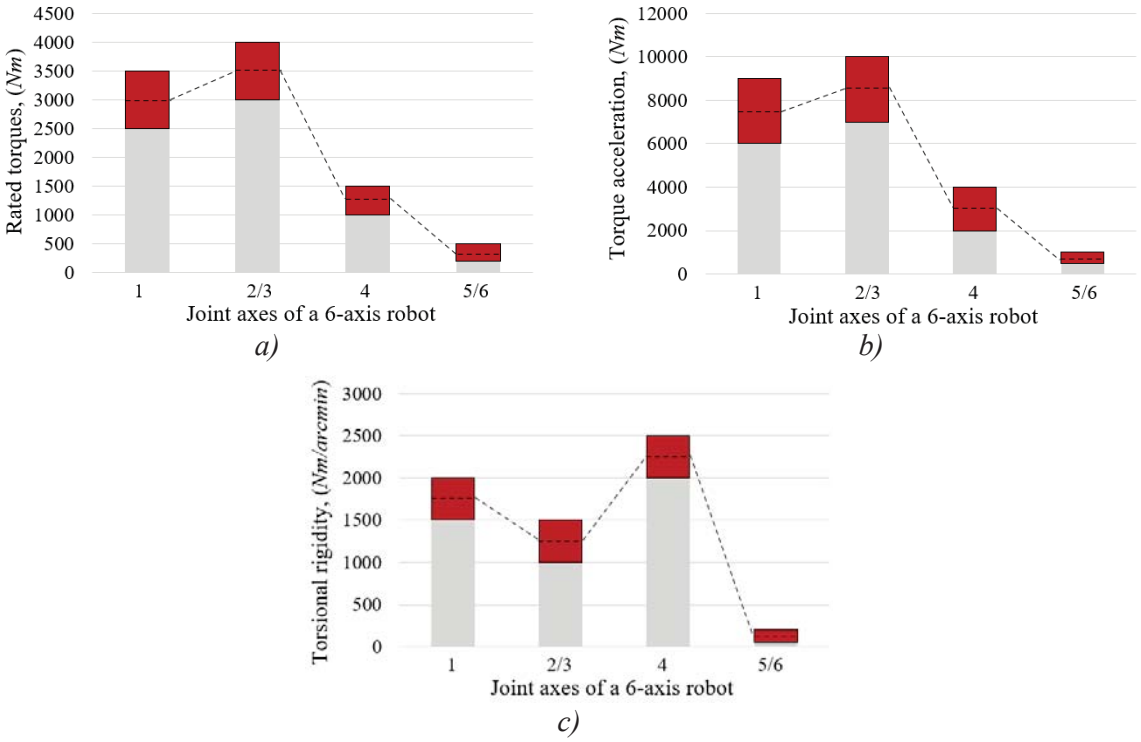


Figure 4. Comparative characteristics of gearboxes in axes: a) rated torques; b) torque acceleration; c) torsional rigidity

4. CONSLUSION

This paper analyses the main factors to be considered when selecting gearboxes for joints of a 6-axis robot. Since gearboxes have a great impact on final performance of industrial robots including speed, acceleration, payload, positioning accuracy and repeatability, the gearboxes generally need to have zero backlash, high torsional rigidity, high torque density, high efficiency and high gear ratios without taking up much space. Each axis has a specific function, therefore, each axis needs a specific gearbox. Considering the fact that the largest loads occur in the first axes: base, shoulder and elbow (especially in the shoulder which carries 70-75% of the total weight of the robot), these axes require gearboxes with high torque density. For other axes, more compact gearboxes can be used, except for axis 4 which requires high torsional rigidity.

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