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Position Singularities and Ambiguities of the KUKA KR5 Robot

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Abstract- Recently in the Robot technological laboratory of the Department of Electrical Engineering and Mechatronics (EEM) of the Faculty of Engineering, University of Debrecen there have been several researches concerning the KUKA and SONY Scara robots. The first part of the paper is a theoretical summary deducing the notions concerning robots from the general system technique. I tried to draft all the definitions as precisely as possible to be able rely on them, only to find out the complexity of the required mathematical apparatus necessary for getting to know the nature of this problem, albeit knowing the mathematics of the Denavit–Hartenberg transformation and the use of the Jacobi-matrix. This paper summarizes the singularity of robot positions and their uncertainty by analyzing the KR5 industrial robot in the Robot Technological Laboratory in the EEM. This paper regards the definition of the ISO 8373:2012 standard as a base and deduces all ideas and relations from this standard. ISO 8373 was prepared by the Technical Committee ISO/TC 184, Automation Systems and Integration, Subcommittee SC 2, Robots and Robotic Devices.

Keywords KUKA KR5; singularities; style; ambiguities.

1. Introduction

At present, more than 1 million programmable industrial robots work in the industries of the world. Programmable industrial robots are suitable for carrying out series of movements and usually move tools and pieces of work seriatim or continuously in accordance with the program in the memory of their controller. Having finished the assigned tasks with their work envelope, they resume their basic position and then repeat the programmed series of movements under the influence of the next starting signal.

Configurations are referred to singular configurations or singularities, where the rank of the Jacobian matrix is not maximal.

Identification of the singularity of the robot arm is an important task on more reason:

- Singularities mark configurations whereby moves of the tool centre point (TCP) in a certain direction cannot be achieved, i.e. the robot arm loses from its degrees of freedom.

- In case of singularities to bounded TCP speeds, unbounded joint speeds belong, because these can extinguish each other.

- In case of singularities to bounded robot arm forces and torques, unbounded joint forces and torques belong.

The singularity of the position of robots and the unambiguous position and orientation of robot arms are some of the most important criteria for carrying out series of movements and for the repeatability and the accuracy of repetition of these movements. This singularity determines the repetition and dynamic accuracy as well as the accuracy of the orientation determined independently from the state of the tools within the work envelope.

6565 of the tool centre point (TCP) in a certain direction cannot be achieved for an undetermined reason, i.e., the robot arm loses its degrees of freedom. In industrial manipulator machines, the position of robot arms defined in relation to each other is determined by their state. The well-selected determination of states and their changes are suitable to avoid this problem.

Singularity issues need to account for its specific deployment and usage in industry and business and how this impacts on the various stakeholders and constituents along the robotic continuum, given the impacts and influences of research and the overriding and even overarching impacts of robotic theorists, practitioners and others involved in this processes, from conceptualization, drawing board stage, design and assembling, mounting and operationalizing and finally its deployment in industry and business for gains.

Mathematically, a Jacobian mathematical matrix formulation can be used to relate the movement in joint space to the movement in Cartesian space. A singularity occurs when the inverse Jacobian becomes singular (determinant = 0).

2. Theoretical Summary

A body will stand underneath a force and its movement will be a constrained movement if its six possible coordinates cannot have optional values and if the connection between them is a constrained condition. The constrained condition includes the accessory geometric conditions delimiting the effect of the free forces affecting a system, which consists of mass points, systems of points and rigid bodies and therefore the movement of the system. Due to constrained conditions, these systems perform a constrained movement. In practice, the movements are usually constrained movements because all elements of a mechanism shall perform a movement designated by another structural element as a force. Forces prescribing constrained movements may be at a standstill, but they can also move (standing and moving forces). Forces are usually functions of the location, time and relative speed.

The mechanism is a moving structure consisting of rigid bodies in connection with each other causing constrained movement. Connected rigid bodies are called the members of the mechanism. A selected member is "the base frame" (the movements of all other members of the mechanism are analysed in comparison to the base frame) The relationship between coordinates can be described by means of the constrained movement equations below if out of six possible coordinates, three indicate a relative displacement (x_{12}, y_{12}, and z_{12}) and the other three indicate angular rotation (φx_{12}, φy_{12}, φz_{12}):

$$s_{12}=f(x_{12},y_{12},z_{12},\varphi_{x12},\varphi_{y12},\varphi_{z12}). \quad (2.1)$$

(Interpretation: member 2 is displaced in comparison to the first member by the x_{12} value, etc.). If the relationship between coordinates depends on time, the previous equation can be described in the form:

$$s_{12}=f(x_{12},y_{12},z_{12},\varphi_{x12},\varphi_{y12},\varphi_{z12,\,t}). \quad (2.2)$$

and these two equations have a serious importance. If the relationship between coordinates does not depend on time, the force is a passive force; if the relationship also depends on time, the force is called an active force.

In the case of a body or mechanism, the degree of freedom is the number of free coordinates independent of each other that evidently determine the position of the body (mechanism). In the case of a force, this means the number of free coordinates independent of each other that evidently determine the position of members in comparison to each other. There are three different degrees of freedom connected with each other.

- Geometric degree of freedom – the degree of freedom of forces as passive forces is indicated by γ (this parameter also means the registration number of the system, force).
- Kinematic degree of freedom - the degree of freedom of forces as active forces is indicated by σ.
- Degree of restriction – the number of restricted coordinates, coordinates in the function are indicated by κ.

The degree of restriction and the degree of freedom are complementary properties, and their sum is always equal to the degree of freedom, with restriction as high as possible.

In the case of force, the number of degrees of freedom is equal to 6, so the

- Geometric degree of restriction:

$$\kappa_g = 6 - \gamma. \quad (2.3)$$

- Kinematic degree of restriction:

$$\kappa_s = 6 - \sigma\,. \quad (2.4)$$

The degree of restriction is equal to the number of constrained movement equations to be written.

A kinematic linkage may be opened (opened kinematic linkage) if its last member is not connected to any previously denoted member. The last member of the robot may work free and not be connected to any other member except the member position in front of it through the joint. This last member (terminal member) is called a peripheral member.

Definition: The main property of six-axis industrial robots functioning as mechanisms with an opened kinematic linkage is that the member has separate drivers on all of its joints. The structure can be described on the basis of the structural formula.

A robot arm having six degrees of freedom (6 DOF) is necessary to grasp a subject in a certain position from an optional direction (3 spatial coordinates + 3 orientation angles). All of these require at least six joints independent of each other. As far as the types of joints are concerned, they may be rotating (R) or dislocating (T). These joints are called elementary joints, i.e., joints having a degree of freedom of one. For one joint it is valid that

$$x_{12}=y_{12}=z_{12}=0 \text{ and } \varphi x_{12}=\varphi y_{12}= 0 \quad (2.5)$$

and $\varphi z12$ can be optimally determined (certainly within geometric limits).

A 6-DOF industrial robot manipulator consists of six joints assuring rotating movements, and the first member is regarded as the base frame because it is fixed and thus does not move during the operation of the robot. This property makes it suitable for bearing the inertia system of the robot called world system of coordinates.

Its structural formula is below.

↓ ↓ ↓ ↓ ↓ ↓

A ← B ← C ← D ← E ← F

The open-linkage robot arms are determined by enumerating the types of joints advancing from the base towards the arm, e.g., RRP. Roll joints perform a rotation around an axis, while slider-crank joints perform a sliding action along an axis. This axis is called the effect axis of the given joint. The position of all joints can be determined by means of only one parameter: roll value or slide value. This is the q = ($q_1, . . . , q_n$) vector called the configuration of the manipulator machine. The number parameters (i.e., joints) are called the degrees of freedom of the robot arm.

The industrial robot is a mechanism consisting of rigid bodies in a constrained connection with each other. Its specialty lies in that all of its members can be driven at the same time, and the movement of a given member can be described in a relatively simple way.

The kinematic linkage is called an opened linkage if both of its ends are connected by only one sequence of segments. The contrary case is referred to as a closed linkage.

Robot kinematics applies geometry to the study of the movement of multi-degree of freedom kinematic chains that form the structure of robotic systems. [1] [2]. A robot usually measures its inner kinematic parameters and joint coordinates directly. Those coordinates measure the position of the joints. We usually denote them as q. The joint coordinate of the revolute joint is denoted as θ, and the joint coordinate of the prismatic joint is denoted as d. The user is interested in the position of the end effector or the position of the manipulated rigid body. The robot has six DOFs and could be described in a number of ways, e.g., by the transformation matrix describing the position of the end effector coordinate system in the world coordinate system. During the operation of the robot, two tasks are possible:

- When the robot parameter vectors are known (direct geometric modelling), the column vector determining the position of moved points shall be determined, and the tool centre point values can be calculated by means of robot joint values (forward kinematic).
- When the column vector determining the position is known, the vector of robot parameters shall be determined (inverse geometric task), and joint values are calculated by means of the tool centre point values.

In the general case, when the trajectory covered by the programmed point is known and on the basis of this knowledge, the vector of robot parameters describing the position and movement of robot arms in comparison to each other shall be determined. This vector is the solution of an inverse geometric task (inverse kinematic).

As far as general embodiment of the connection of robot arms by means of joints is concerned, the connection produces the connection chain shown in Fig.1.

The position of the coordinate systems fixed to arms with respect to their transformation into each other can generally be presented as shown in Fig. 2. Let us regard the two coordinate systems, one succeeding the other, determined with the features indicated in Fig. 2.

$$R_{i-1,i} = \begin{bmatrix} \cos q_i & -\sin q_i \cos \alpha_i & \sin q_i \sin \alpha_i \\ \sin q_i & \cos q_i \cos \alpha_i & -\cos q_i \sin \alpha_i \\ 0 & \sin \alpha_i & \cos \alpha_i \end{bmatrix} \quad (2.6)$$

The beginning point of the (x_{i-1}, y_{i-1}, z_{i-1}) coordinate system shall be moved a distance P so that the two coordinate system cover one another.

$$P = \begin{bmatrix} a_i \cos q_i \\ a_i \sin q_i \\ d_i \end{bmatrix} \quad (2.7)$$

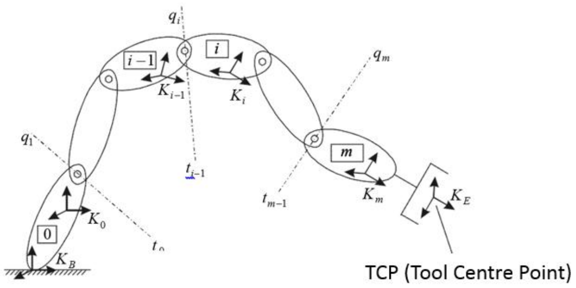

Fig.1. Principal scheme of a robot having an opened chain without embranchment [3]

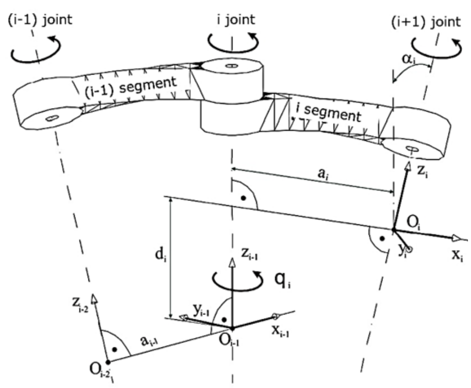

Fig.2. Denavit–Hartenberg method [4].

The $R_{i-1,i}$ matrix can be extended with the P vector. When using homogeneous coordinates after rotation around the xi and z_i axes and movement along the x_i, y_i and z_i axes, we obtain the so-called Denavit–Hartenberg matrix by simultaneously interpreting the rotation and movement [5].

$$DH_{i-1,i} = \begin{bmatrix} cosq_i & -sinq_i cos \propto_i & sinq_i sin \propto_i & a_i cosq_i \\ sinq_i & cosq_i cos \propto_i & -cosq_i sin \propto_i & a_i sinq_i \\ 0 & sin \propto_i & cos \propto_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2.8)$$

The transformation of joint coordinates into world coordinates occurs by means of the Denavit–Hartenberg transformation matrix. Denavit and Hartenberg published this method in 1955, so it is named Denavit–Hartenberg method [4]. The substance of the method lies in transforming a system of coordinates into another system of coordinates by means of two translation and two rotating movements. The Denavit–Hartenberg parameters used in robot manipulator machines are the distances d and a and the angles α and q.

The transformation between coordinate systems (j and k) can be written by means of the

$$\bar{j} = \boldsymbol{DH}_{jk}\bar{k} \quad (2.9)$$

matrix equation.

3. The K5 Robot

The KR5 robot consists of six joints that assure rotating movements, so its basic configuration is RRR. The recurring elements of the robots are robot arms and joints connecting arms. The connection object is oriented. One joint connects two arms, and one arm connects two joints. The KR5 robot consists of six joints that assure rotating movements, and the first member is regarded as the base frame because this member is fixed and does not move during the operation of the robot. This property makes it suitable for bearing the inertial system of the robot called the world coordinate system. Fig.3 shows the coordinate systems of robot. For controlling KUKA robots, four types of Descartes systems of coordinates are determined:

- WORLD
- ROBROOT
- BASE
- TOOL.

All robots have a controlling unit, the most important task of which is regulation of driving, as mentioned before in accordance with incoming signals and previously programmed commands. The Controller Cabinet has been given the name KUKA KR C2.

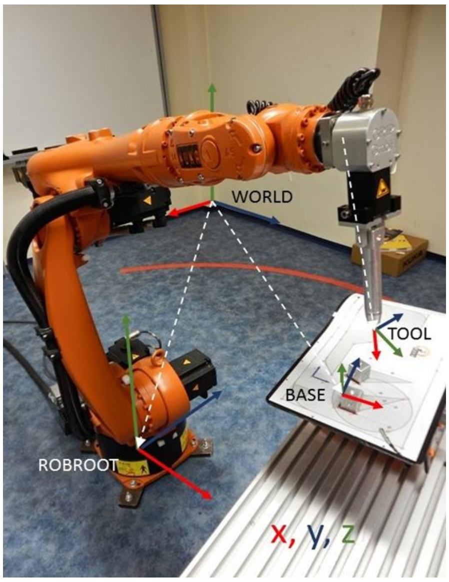

Fig.3. Robot systems of coordinates.

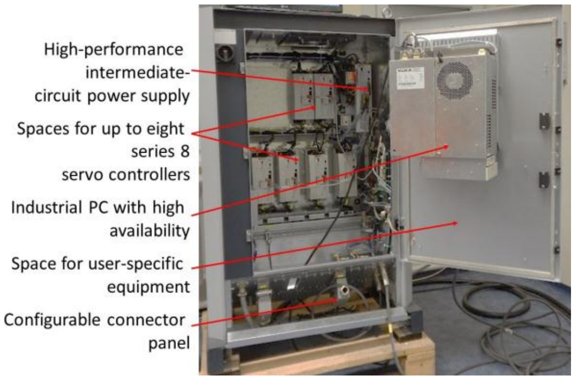

Fig.4. KUKA KR C2 controller cabinet

Two processors are in the Controller Cabinet because two servo units, two processors interpreting and running the program as well as another moving processor coordinating the axis movements of the robot are necessary for driving servo-motors because the synchronisation of the movement of six axes is an important task. The controlling unit is connected with the robot by a CAN bus bale of DeviceNet type. This unit is a serial bus system enabling the contact between the robot and tool connected to it (reception and sending).

Industrial robots can be classed into two groups on the basis of their programming. Different robots carry out different working processes, so different working processes require different programming techniques. The two large groups are ON-LINE and OFF-LINE programming. KUKA can be programmed by using both of these programming methods using KRL 5.5 (KUKA Robot Language 5.5).

4. Synchronising Problems in Different Coordinate Systems

A serious problem may arise in planning the movement of the KRS robot when right-angled coordinate systems (WORLD, ROBROOT, BASE, TOOL) are used for the plan as the actual movement is realized in a polar coordinate system due to the structure of the robot (robot with opened chain and without embranchment) and the rotating movement of its arms in a polar coordinate system. This property means that the position and orientation determined in the right-angled coordinate system are determined by the angular position of the 6 joints of the 6-axis robot.

In any case, when the programmer employs a right-angled coordinate system to program the movement of the robot, the controller transforms the values determined in the right-angled coordinates into the joint angular turn of the arm and then processes the feedback signal from the motor conducting the movement. A permanent coordinate transformation (Fig. 5.) occurs in the controller during the movement.

The situation gets more complicated, as 4 right-angled coordinate systems (WORLD, ROBROOT, BASE, TOOL) can be used, and positions in each can be transformed into the others. The position and orienta,tion of the robot can in principle be defined in the following coordinate systems. In the AXIS-specific coordinate system (A), each axis can be moved individually in a positive or negative direction. The ROBROOT coordinate system (R) is a Cartesian coordinate system that is always located at the robot base. It defines the position of the robot relative to the WORLD coordinate system. By default, the ROBROOT coordinate system is identical to the WORLD coordinate system. ROBROOT allows the definition of an offset for the robot relative to the WORLD coordinate system. The WORLD coordinate system (W) is a permanently defined Cartesian coordinate system. It is the root coordinate system for the ROBROOT and BASE coordinate systems. By default, the WORLD coordinate system is located at the robot base. For achieving the 3 degrees of freedom in positioning, the base configuration of the robot is necessary. The axis-specific coordinate of the robot is a scalar value defining the relative position of a segment of the kinematic match in comparison to the other segment. In the rotation joint, the joint coordinate corresponds to the rotation angle of the joint. The axis-specific coordinate of the robot is indicated as follows:

$$q\_i \qquad i=1,2,\ldots.n \tag{4.1}$$

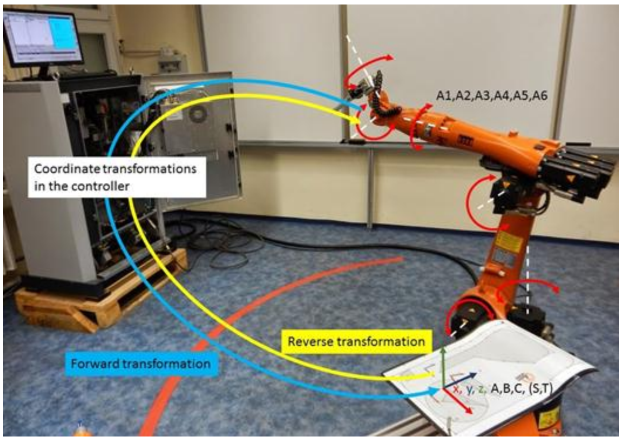

Fig.5. Coordinate transformations in the controller.

While the vector of coordinates is:

$$q = [q_1\ q_2 \ldots\ldots q_n]^T \tag{4.2}$$

The axis-specific axis of the KR5 robot, which has 6 degrees of freedom. All axis-specific coordinates can change within certain limits:

$$q_{imin} \leq q_i \leq q_{imax} \tag{4.3}$$

During the positioning of the joints, an important condition is that the orientation of the effector also changes so that the orientation of the effector will be corrected after all movements occurring in axis-specific coordinates. Robot coordinates define the position and orientation of the manipulator machine of the robot in a Cartesian (Descartes) right-angled coordinate system. This coordinate system is fixed to the base of the robot. The position of the effector can be represented as the three Descartes right-angled coordinates (x, y, z). In practice, the world coordinates and robot coordinates correspond to each other. In the coordinate system of the robot, the lower plane of the robot base and the cutting point of the rotation axis (first axis) of the first motor define the origin, while the x axis is the bisector of the angle defined by the end points (q_1min and q_1max) of the first axis and the origin. The orientation of the effector can be represented as modified Euler angles: φ, θ, ψ. These angles define the angular rotation of the moving coordinate system fixed to the effector with respect to the robot coordinate system. The effector has its own coordinate system, termed the TOOL coordinate system.

The TOOL coordinate system (T) is a Cartesian coordinate system that is located at the tool centre point. By default, the origin of the TOOL coordinate system is located at the flange centre point (in this case it is termed the FLANGE coordinate system.) The TOOL coordinate system is offset from the tool centre point by the user. The optional position and orientation of a robot can be represented in the world coordinate system as follows:

$$S_W = [x, y, z, \varphi, \theta, \psi]^T \tag{4.4}$$

Where,

- The x, y, z coordinates represent the vector (position) from the origin of the world coordinate system to the TCP (tool coordinate system);
- The φ, θ, ψ rotations indicate the rotation of the axes of the world coordinate system in parallel with those of the tool coordinate system (positioning).

If the world coordinates and robot coordinates correspond to each other as,

$$O_W = O_R \text{ and } x_W = x_R;\ y_W = y_R;\ z_W = z_R, \tag{4.5}$$

The S_W vector will correspond to the optional position and orientation of the robot in the ROBROOT coordinate system:

$$S_W=S_R. \tag{4.6}$$

5. Ambiguities

During the solution of the inverse kinematic task, the number of solutions is > 1. This means that the TCP is in the appropriate position, but the position of the arm is not unambiguous. As an example, let us consider Fig. 6. The example in the upper part of the figure shows that, with respect to joint 2, joint 5 can achieve the same position in two different ways, depending on the relative positions of joint 2 and 3. In the example in the lower part of Fig. 5, it is clear that the grasping position will not change as long as a turn by axis 4 in any direction is countered by the same degree of turn by axis 6 in the opposite direction. In this latter case, the ambiguity of position value of the arm is not two but infinite, and this state can be maintained not only in the case of discrete values but also permanently over time. The problems concerning robot arm ambiguities of position can only partially be managed by the KRC 2 robot controller of the KUKA KR5 robot and the KRL 5.5 robot programming language. During programming, the positions of an arm in comparison to each other (S Status) and the direction of a turn (T Turn) can be separately given. The entries "S" and "T" (Fig.7) in a position (POS) specification serve to select a specific, unambiguously defined robot position when several different axis positions are possible for the same point in space (because of kinematic singularities).

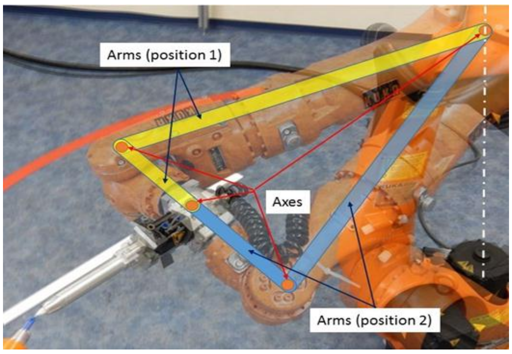

Fig.6. Examples of ambiguous robot kinematics.

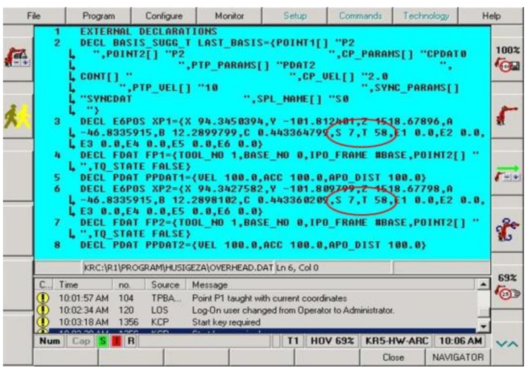

Fig.7. Status and Turn.

6. The Singularity

The singularity is defined as the configuration of a robot position that is accompanied by the loss of a degree of freedom. Configurations for which the rank of the Jacobi matrix does not have the maximum value are called singular configurations, or singularities. The examination of Jacobi matrix ranks is important in the inverse velocity aspect, as it becomes obvious that, in the whole rank case, the solution can be calculated very easily. A further denomination is that the singularities of the B(α) matrix are termed representative singularities [6].

It can be easily shown on the basis of the formula [6]:

$$B(\alpha)=\begin{bmatrix}\cos\psi\sin\theta & -\sin\psi & 0\\ \sin\psi\sin\theta & \cos\psi & 0\\ \cos\theta & 0 & 1\end{bmatrix} \tag{6.1}$$

That, in the case of $\sin\theta\neq 0$, B(α) can be inverted, which is important for the complete rank state on the basis of the equation

$$J_a(q)=\begin{bmatrix}I & 0\\ 0 & B(\alpha)^{-1}\end{bmatrix}J(q) \tag{6.2}$$

These equations show that the singularities of the analytic Jacobi matrix include representation of the singularities of the geometric Jacobi matrix. According to its definition, the $6\times n$ J(q) Jacobi matrix determines a value

$$\xi = J(q)\dot{q} \tag{6.3}$$

mapping between the *dq/dt* vector of the velocity of the joint and the

$$\xi = (\upsilon,\omega)^T \tag{6.4}$$

vector of the velocity of the arm.

In the standard KUKA kinematic system, a distinction is made among 3 different singularity positions. These are the overhead singularity, the extended position and the wrist axis singularity. One characteristic of a singularity is that an unambiguous reverse transformation (conversion of Cartesian coordinates to axis-specific values) is not possible, even though Status and Turn are specified. Small Cartesian changes in the immediate vicinity of a singularity give rise to major changes in the axis angles [7]. The wrist root point, located at the intersection of axes A4, A5 and A6, is positioned directly on axis 1 (Fig. 8).

The position of axis 1 cannot be determined unambiguously by means of the reverse transformation and can thus have any value. If the end point of a PTP motion results in the overhead singularity, the controller offers the following options:

- Axis 1 is moved to "0" degrees (default position) during the PTP motion.
- The axis angle for axis 1 remains the same for both the start point and the end point.

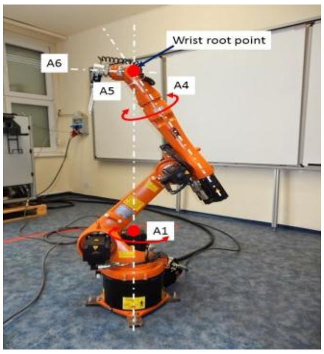

Fig.8. The wrist root point, located at the intersection of axes A4, A5 and A6.

Figure 9 shows when the extension of A2-A3 intersects the wrist root point. In this case, the robot is at the limit of its work envelope. Although reverse transformation does provide unambiguous axis angles, low Cartesian velocities result in high axis velocities for axes 2 and 3.

In the wrist axis singularity (A5 position, Fig. 10) the axes 4 and 6 are parallel. It is not possible to unambiguously determine the positions of these two axes by means of reverse transformation, as there is an infinite number of axis positions for A4 and A6 for which the sum of the axis angles is identical.

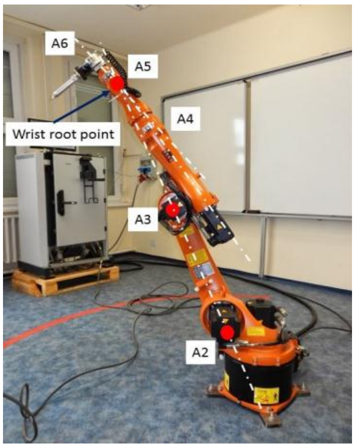

Fig.9. The extension of A2-A3 intersects the wrist root point.

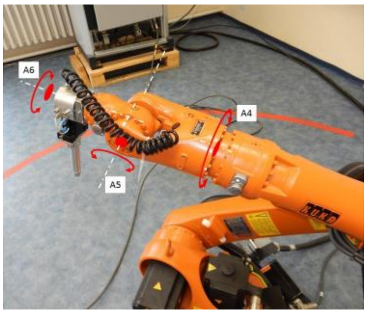

Fig.10. Axes 4 and 6 are parallel.

7. Conclusion

This paper has at length delved into the basic aspects of Different singularity positions Standard 6R 6DOF kinematic system. The subject is not only complex and far entailing but also evolving and dynamic one, wherein the technology is subject to major changes over time and new technoogo9 that supplants earlier ones are occurring on recurrent and periodic basis so it is rather difficult to place best industry practices in the realms of position Singularities of 6R 6DOF of Robots in its proper and definitive perspectives. Moreover, it is also necessary to admit that globally, different manufacturers, assemblers and sellers have different norms and practices with regard to the overwhelming and preponderance of Standard 6R 6DOF kinematic system and most robust systems that are diligent, committed and laborious have withstood the test of time and changing technology in these domains The realms of Standard 6R 6DOF kinematic system are indeed major issues that need to be considered in the realms of manipulators and it is also important to consider the preponderance of major issues like that of representations of designs for Jacobean theories and its enforcement in the realms of Standard 6R 6DOF kinematic system.

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