PATH PLANNING OF ROBOT WELDING TRAJECTORIES USING SCREW THEORY

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Abstract.
This article presents a methodology for trajectory planning in robot welding applications, which handles parts with geometric restrictions . Differential kinematics are calculated using the screws theory and an optimal welding position (plain position) is obtained when defining the welding sequence. The latter is the major contribution of the proposed methodology, since previous work have only explored the problem of relative positioning between torch and welding groove, using the robot as a tool for the welding. While those approaches have made use of Kinematic relations between the mechanisms for positioning the part and the torch, they have not taken into account the plain condition for the welding as an optimization criteria. In this work, the concept of virtual kinematics is used in a systematic and unified approach to calculate differential kinematics of the manipulators in order to guarantee that positioning restrictions will be satisfied.

Keywords: *Cooperative robots, virtual chains, Screw theory*

1. Introduction

Different approaches have been considered in robotics to represent the relative position and orientation between manipulator links and end effectors. The widely used approach was proposed by Paul (1977) and is based on the notation of Denavit and Hartenberg (1955) for the definition of the relationship between spatial coordinates of manipulator joints.

In applications on which parts have geometric restrictions, as in the case of welding, the torch positioning along the welding path plays a key role in the quality of the bead. Some authors, Bolmsjö and Nikoleris (1993) and recently Pashkevich et al. (2003) had dealt with the problem of relative positioning between the torch and the welding groove, using the robot as tool for the welding. Although they had explored the kinematic relations between the mechanisms for positioning the part and the torch, their approach did not take into consideration geometric restrictions of the part.

Methods based in kinematic relations face difficulties to handle problems such as robot singularities and several techniques have been proposed in the literature to overcome these problems. Mathematically, when a manipulator is in a singular position, the determinant of this Jacobian is null and its inverse does not exist, thus disabling its movement.

To deal with singularities, the approach presented in this paper uses the concepts introduced by Campos (2003) for the calculation of Jacobian of serial manipulators, based on the theory of screws, Hunt (2004) and Tsai (1999). This technique leads to Jacobians easier to be inverted.

Additional, some modifications to the original kinematics chain are included (the so called virtual chains as defined by Campos (2004)), so that an optimal planning of the relative movement for the robots carrying the torch and the part can be achieved.

The proposed method gets as inputs the part's geometric restrictions, the torch's position and orientation and a welding trajectory in the part. Based on this, an optimized trajectory for the welding robots is generated, aiming at plain position during the welding process.

2. Screw Theory

The screw theory is an important tool in the analysis of kinematic and static chains. Its formulation is based on the theorem of Mozzi 1763 and systemized by Ball in 1900. The geometry kinematics aspects have been developed by Hunt (2004) and Tsai (1999). Additionally the theorem of Chasles, 1830, establishes that "Any rigid body displacement can be realized by a rotation about an axis combined with a translation parallel to that axis.". The complete movement is called twist and represented by **$** .

A body with movement around an axis instantaneously fixed with respect of the inertial reference frame O is shown in the Fig. 1. This instantaneous axis is called the screw axis and the rate of the magnitudes of the translational and angular speed is called the pitch of the screw h and represented by the equation $h = \|\tau\| \backslash \|\omega\|$.

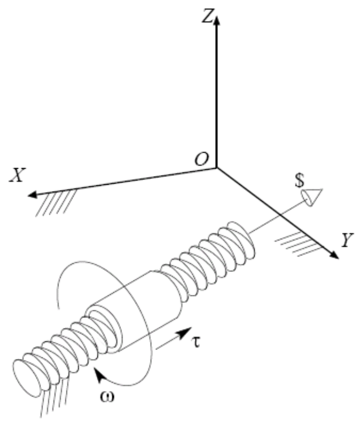


Figure 1. Screw movement, combining rotation and translation

The complete movement of a rigid body in relation to an inertial frame is expressed by a screw composed for a pair of vectors, $\hat{\$} = (\omega; v_p)^t$, or in terms of screws (l, m, n, p^*, q^*, r^*). The vector $\omega = (\omega_x, \omega_y, \omega_z)$ represents the angular velocity of the body with respect to the inertial frame. The vector $V_p = (v_{px}, v_{py}, v_{pz})$ represents the linear velocity of a point P attached to the body which is instantaneously coincident with origin O of the reference frame.

Consider a twist given by $\$ = (\omega, V_p)^T = (L, M, N, P^*, Q^*, R^*)^T$ then the correspondent normalized screw $\$$ may be defined as a pair of vectors, namely, (L, M, N) e (P^*, Q^*, R^*) given by,

$$\$ = \begin{bmatrix} \frac{L}{\psi} \\ \frac{M}{\psi} \\ \frac{N}{\psi} \\ \frac{P^*}{\psi} \\ \frac{Q^*}{\psi} \\ \frac{R^*}{\psi} \end{bmatrix} = \begin{bmatrix} L \\ M \\ N \\ P^* \\ Q^* \\ R^* \end{bmatrix}$$

and

$$\begin{bmatrix} L \\ M \\ N \\ P^* \\ Q^* \\ R^* \end{bmatrix} = \begin{bmatrix} S \\ S_o \times S + hS \end{bmatrix}$$

where S is the normalized vector parallel to the screw axis.

Depending on the body, if there are no points of the body coinciding with the frame origin O, as in Fig. 1, a ficticious extension may be added to the body such that a point in this extension, named point P , coincides with the origin O, Fig. 2.

The vector (V_p) it is formed by two components of speed: a) a velocity component parallel to the screw axis represented by $\tau = h \times \omega$; and b) a velocity component normal to the screw axis represented by $S_o \times \omega$ onde S_o, where S_o is the position vector of any point at the screw axis represented vectorially in the system of Fig. 2.

A twist may be decomposed into its amplitude ψ and its corresponding normalized screw $\hat{\$}$ by,

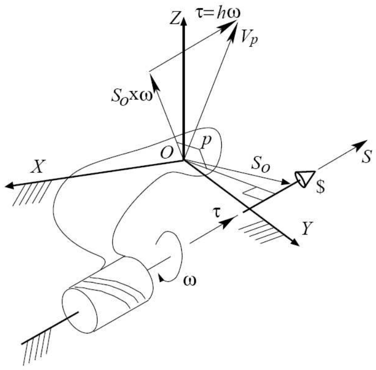


Figure 2. Twist components for generic links

$$\$ = \hat{\$}\psi$$

The twist amplitude ψ is either the magnitude of the angular velocity of the body, $\|\omega\|$, if the kinematic pair is rotative, or the magnitude of the linear velocity, $\|V_p\|$, if the kinematic pair is prismatic. When the movement of the body combines rotation and translation the magnitude of twist is the magnitude of the angular velocity of the body $\|\omega\|$.

The movement between two adjacent links, belonging to a kinematic chain, may be also represented by a twist. In this case, the twist represents the movement of link i with respect to link $(i-1)$. In Robotics, generally, the differential kinematics between a pair of bodies is determined by either a rotative or a prismatic kinematic pair. For a rotative pair the pitch of the twist is null (h = 0). In this case the normalized screw for a rotative pair is expressed by,

$$\hat{\$} = \begin{bmatrix} S \\ S_o \times S \end{bmatrix}$$

The pitch of the normalized twist that represents the movement of a body determined for a prismatic pair is infinite $h = 1$ and the normalized twist for a prismatic pair is reduced to

$$\hat{\$} = \begin{bmatrix} 0 \\ S \end{bmatrix}$$

The twist components are functions of the reference frame where is represented. Frequently the twist is represented in different frames , for that is used, as tool, the homogeneous transformation of twist.

3. Virtual Chains

The virtual kinematic chain is essentially a tool to obtain information about the movement of a kinematic chain or to impose movements on the kinematic chain which is named real chain. It can be considered a kinematic chain that satisfying the following three properties:

- the virtual chain is serial and composed by links (virtual links) and joints (virtual joints) ;
- it has joints whose normalized screws are linearly independent;
- it does not change the mobility of the real kinematic chain.

Using screws it can be selected different frames for representing the movement between bodies. Thus, it is possible to represent the movements of the virtual joints in a convenient frame to obtain more simple twist.

In this article the focus is in use of the virtual chains for attainment of the information of movement of the real chain kinematics changing the characteristics of the movement of the involved real kinematic chains in the trajectories of welding with robots.

3.1 Joint orientation

A free body in the space can be defined by its position and orientation in relation to a inertial frame. For the case of the welding, the position and orientation of the torch and the part are basic and some restrictions are determinative for the execution of the weld bead. In this article, the positioning of the torch in relation to weld part and the planning of the weld trajectory through the positioning of part in relation to the plain position of welding,Fig. 3, are adopted as restrictions. In the practical one it is suggested:

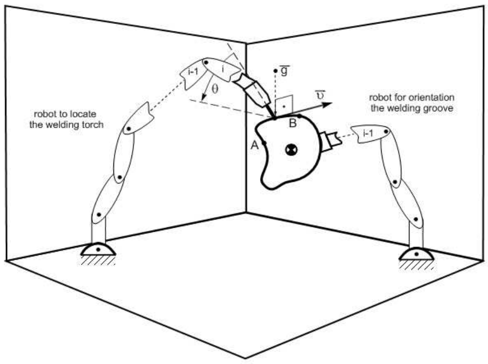


Figure 3. Welding Restrictions

> *"the welding must be guided in relation to the horizontal plan of form that the torch remains in the vertical line and be pointed to dow."*

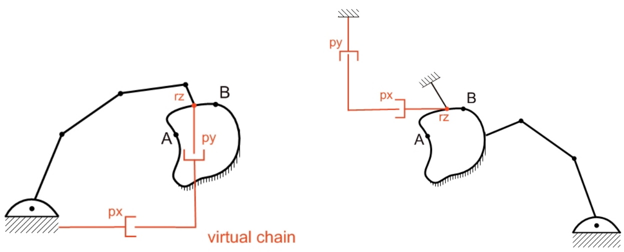
In this condition the Z axis of reference frame is vertical [1] and consequently the X and Y axis is in the horizontal plane. The first robot, that loads the torch, defines the orientation in relation to the part and is restricted to the condition of that the torch remains in the vertical line and pointed to dow. The position is coordinated by another robot that guarantees that the vector welding velocity is perpendicular to the acceleration vector gravity ($\overrightarrow{g} \perp \overrightarrow{v}$).

It fits to point out that the angle θ must approximately be constant in all trajectory, thus the orientation of the torch in relation to part and that the acceleration vector gravity is perpendicular to the direction of the welding speed vector.

3.2 Solution is dependent of the degrees of freedom

Given one determined part, in order to execute the welding with robots, it in adequate way must be located it and be guided. The use of solutions developed for manual welding does not respect the imposed conditions to locate and to guide the part due the lack of degrees of freedom.

For illustrate this situation the kinematic chains is represented in bidimensional space. Two other virtual chains are add to the real kinematic chains to coordinate its movements externally of form to respect the kinematic restrictions imposed by the process, Fig. 4.



(a) fixed part (b) mobile part

Figure 4. Virtual chains and degrees of freedom

The task of conventional welding can be separated in two cases. In the first one it is had fixed part and the robot as positioner of the torch. It is concluded that it does not have conditions to delineate the trajectory for absence of degrees of freedom Fig. 4(a), then it is needed to locate the welding groove three degrees of freedom shown by the virtual chain,p_x,

[1]opposed to the direction of the acceleration vector gravity $\overrightarrow{g}$

p_y and r_z. In the second one had part in movement and the torch fixed, Fig. 4(b), is needed three auxiliary movements more to execute the task and again it is not obtained to delineate the trajectory.

To delineate the trajectory two robots in cooperation are used, applying the screw theory and the concept of virtual chains for the treatment of the kinematic restrictions, of position and relative orientation of the torch in relation to the welding groove.

3.3 Application of virtual chains

The use of suitable solutions of the manual welding in the welding with robots does not solve the problem of the restrictions imposed as contour conditions, considers the use of the following structure of virtual chains, Fig. 5.

The addition of two virtual kinematic chains increases the number of degrees of freedom of the system and allows the treatment of the restrictions. One kinematic chain added to welding robot, with the following degrees of freedom, p_x, p_y and r_z responsible for the position and orientation of the torch in function of the geometry of the part. Another kinematic chain added to the positioner robot, with the following degrees of freedom, $p_{x'}$, $p_{y'}$ and $r_{z'}$ responsible for the positioning of welding groove in relation to the ground, to guarantee the delineate the trajectory.

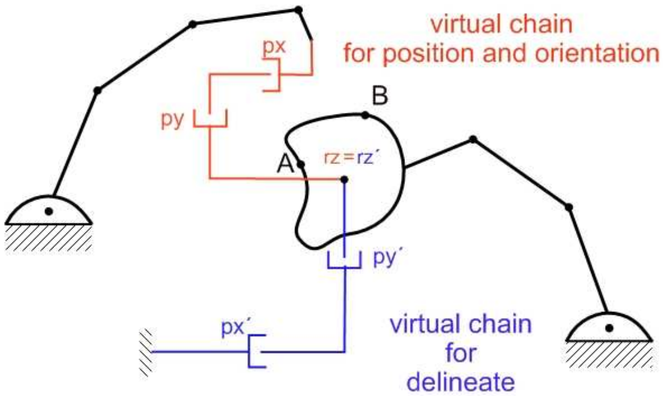


Figure 5. Virtual chains arrangement

For the application in the path planning of welding the structure presented in the Fig. 5 allows the calculation of the differential kinematics, to deal with the singularities in the trajectory and the fulfilment of the contour conditions of contour for the problem (Item 3.1).

4. Bidimensional example

Imagine two serial robots working in plan XY operating over a plain part, Fig. 6. The objective of the path planning is to effect the movement coordinated between the part and the torch to cover the trajectory of welding between points 2 and 3, of the represented plain plate in the figure. Both must work in synchronism, for in such a way must be added two virtual chains (Fig. 5): the first responsible one for the referring calculations to the end effector of robot 1. Second to connect the end effector of robot 1 with robot 2, calculating the interactions of position and velocities between them.

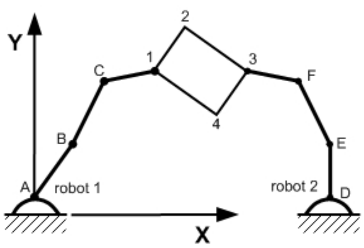
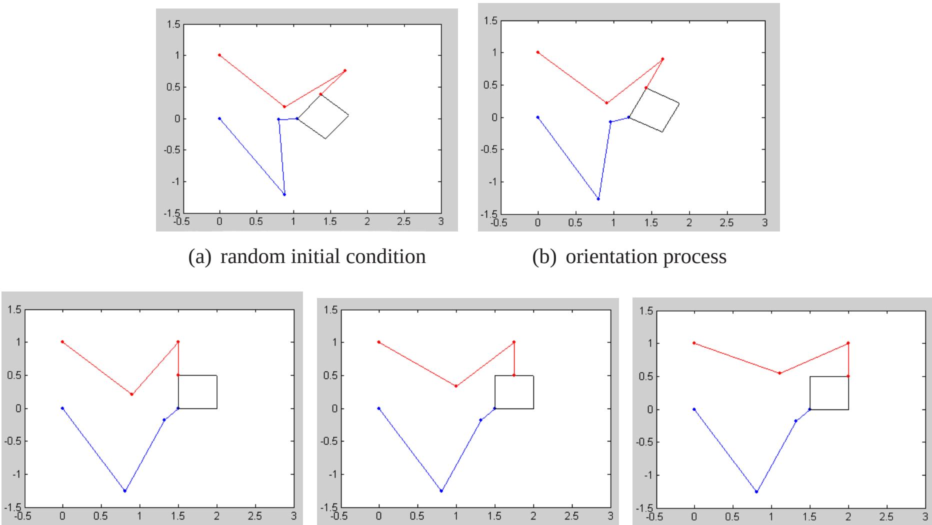


Figure 6. Cooperative robots

In this article, is presented the procedure adopted without describes details of the calculations. This technique was implemented for a generic case, for Campos (2004), and adapted in this article for the case of the welding with robots. The Fig. 7 presents the results of the simulation made in MATLAB, where it describes the movements of the robots.

The sequence of figures describes the positioning of the robots during the execution of simulation the trajectory. In the

Fig. 7(a) the initial condition of the system is described, in the Fig. 7(b) the rearrangement of the edge in relation to the reference frame, in fig. 7(c) reached it initial condition of movement of the torch and initiates it welding, in figures 7(d) and 7(e) the welded is made in the plain position. While the system remains outside of the plain condition, figuras 7(a) and 7(b), the system does not put the torch in movement.



(a) random initial condition

(b) orientation process

(c) plain condition

(d) welding in plain position

(e) final position

Figure 7. Trajectory evolution

5. Conclusion

In this article a methodology for the planning of trajectories of welding with robots is presented. Being based on the use of the screw theory and the virtual kinematic chains, one minimizes the effect of typical singularity and positioning of the welding.

It is concluded from the results presented in the simulation, that the imposition of movements by means of virtual kinematic chains for the robots revealed efficient in the planning of welding trajectories.

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