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Development of Trajectories Through the Kalman Algorithm and Application to an Industrial Robot in the Automotive Industry

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ABSTRACT This paper presents a method for optimizing the trajectories of robotic arms having manipulators with six degrees of freedom (DOFs) and spherical wrists. The trajectories are optimized by maximizing the manipulator performance (manipulability). For this purpose, kinematics models of the robot arms are defined, such that they can be integrated into an algorithm based on the Kalman filter. This algorithm is implemented through the simulation of trajectories in a serial industrial robot, which is a robotic arm with six DOFs and a fitted welding tool with a material contribution. During the trajectory optimization for such a manipulator robot, the orientation of the welding gun (e.g., the position of the final effector) must be preserved to guarantee correct welding. Applications of this method to two trajectories in the automotive industry are presented, and remarkable improvements in the performance of the manipulator itself are observed. The results obtained demonstrate that the proposed algorithm is an appropriate method for optimizing trajectories because of its various advantages, such as ease of implementation and states of calculation based only on the previous states. Therefore, this method allows the trajectories to be optimized in the work environment of the robot once the kinematic parameters of a robotic manipulator arm are known.

INDEX TERMS Algorithm, Kalman filter, manipulability, simulation, trajectory optimization

I. INTRODUCTION

The current situation of the automotive industry and the market demand for new products make wise investments essential in car factories. In economic terms, this investment involves some risk. Therefore, exhaustive studies and simulations must be conducted to validate an investment before implementing it. The automotive industry is characterized by having a high degree of automation in its processes, with the most automated process being the body shop. A body shop is where the body of the future vehicle is manufactured. This is an extremely complex task, wherein the difficulty is based on the need for all the parts, subsets and sets that compose it to be correctly assembled. To address this difficulty, a body shop generally has degrees of automation close to 95% [1]. A significant part of this automation is achieved with robot manipulators that perform different functions.

One of the main applications of robot manipulators in the body shop is welding through electric arc and shielding gas. This technique is widely used, largely due to the reliability of the union, to the accuracy of it and to the low cost in relation to other processes of the union [2]. Welding through robots is often used in the automotive industry to eliminate human factors in the process. The use of robots generates higher productivity ratios, higher quality and reduced labor costs [3]. To ensure that an optimal welding process is performed, a programming adapted to the quality of the union of all the relevant parameters, such as the current rating, voltage, speed of contribution of the thread, speed of welding, flow rate of the shielding gas and arc length, is necessary. In addition, since the welding is carried out by an industrial robot, the performance of the robot manipulator arms must be optimized to guarantee a high productive value.

To optimize the performance of robotic arms, the concept of the *index of performance* [4] was introduced in the 1980s.

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This index refers to a scalar magnitude that allows the behavior of a robot to be evaluated based on established criteria. This index of performance has been the focus of several studies because of its importance in robotic arm optimizations. Various authors have presented different criteria for its calculation. Ma and Angeles [5] presented the concept of dynamic *isotropy* to evaluate the index of performance. This concept of dynamic isotropy or index of dynamic conditioning is defined as the deviation for minimum squares between the matrix of generalized inertia and an isotropic matrix. Kumar and Waldron [6] suggested calculating the index of performance of a manipulator by tracking the surfaces that delimit the working space of the manipulator. Bicchi *et al.* [7] presented a method to obtain the index of performance by considering a robot system as a set of cooperative members.

Many of the indexes of performance are defined using a Jacobian matrix. When the values that compose the matrix are not homogeneous, i.e., there are robots that must control position and orientation (as in this case), the results regarding these indexes of performance are not valid [8]. Different authors have presented different solutions, such as the ellipsoid of speed [9], the number of condition [10], the minimum singular value [11], and the index of manipulability [12], to solve this problem.

The goal of this paper is to optimize the times of route, optimize the trajectories and maximize the manipulability. We focus on the final effector and assume that the welding gun must present the position values, speed and orientation to achieve a correct welding performance.

In this study, the manipulability combined with an estimator is used as a basis to optimize the manipulator because this index aims to measure the capacity of the manipulator to generate speed in the final effector.

Previous studies have also aimed to optimize the times of trajectory and maximize the performance of the manipulator and have presented other interesting techniques. Among these studies, the following are highlighted. Glorieux *et al.* [13] presented a new methodology to optimize the trajectory and obtain the coordination of cyclic systems for multi-robots. The setting of the speed as well as the time delays are used to coordinate the robots such that they operate in their proximity and to prevent collisions. The new element that Glorieux et al. presented is the model of non-linear programming optimization, wherein the experimenter is in charge of adjusting the coordination of multiple robots directly during the optimization of the trajectory, which allows the robot optimization to be the only problem. Wu *et al.* [14] presented a design approach based on genetic algorithms to control the trajectory of a robotic arm based on the optimization of several criteria. The described methodology is based on the problem of inverse kinematics, and it considers the minimization of both the operating time and the sum of all rotation changes during the operation cycle. However, the genetic algorithm can converge prematurely or not converge at all. Therefore, the chosen initial parameters must be carefully considered. Lian *et al.* [15] suggested a new method for planning trajectories based on genetic algorithms. In this method, a polynomial based on the cubic interpolation of Hermite is applied to bring the temporary records of the trajectory over in the working space. Estevo et al. used a genetic algorithm that applies the cubic interpolation of Hermite and determines the degrees by which the resulting polynomial is louder than the original. Rubio *et al.* [16] approached the optimization of the trajectories of a manipulatory robot in two steps. The first step applies an algorithm of polynomial splines that considers a trajectory without obstacles, whereas the second step accounts for real obstacles and thus allows the proposed algorithm to progress. A limitation of this application is that it must consider trajectories that are soft and near the optimum time.

All these methods use stochastic techniques to optimize the respective goal functions, and all require various assumptions, such as linearity or convexity, to hold them. However, in this article, the search for the results is done in a completely different way to the previous methods. The optimization problem is considered as a measurement process and subsequent correction in which the initial condition will always be the improvement of the data from the previous estimation. This method offers the advantages of stochastic techniques.

This process of measurement and subsequent correction of the deviation is based on the Kalman method [19]. As will be seen later, this method gets high quality solutions and whose main advantage is the scarce need to know many design parameters. In addition, this method is applicable even in cases where it was not possible to define the objective function analytically. As has been observed in the literature review, the most commonly used methods with single criteria function planning are adapted genetic algorithms, simulated annealing methods, evolutionary algorithms or B-spline cubic interpolations.

In the review of the literature it has been stablished that Kalman method, in the field of robotics, has been generally used in applications with mobile location positioning robots or global positioning systems [20]–[22] because of its ability to predict past, present or future states. This is due to the design complexity of the parallel robots.

Hence arises an opportunity to research using the Kalman method for serial manipulators and the treatment of its solution as a measurement process.

As is known the Kalman method is it based on objective algorithm of data searching the optimal function recursively. Its implementation shall be a normal probability density function and a Kalman estimator.

Since the serial manipulators are widely used in the industry due to its high efficiency, high versatility and low cost [17], [18], is decided to delve into this article on new methods for their optimization. This contribution will be made through study of robot manipulation, which allow to analyze the quality of the obtained solutions and therefore the validity of the method.

This implementation of the Kalman method through the concept of manipulability will be for two real robot

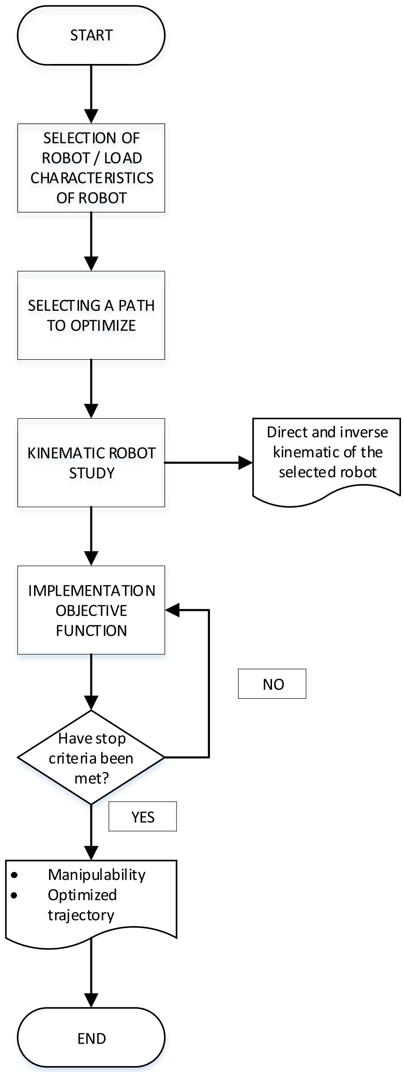

FIGURE 1. **Flowchart for the optimization of trajectories.**

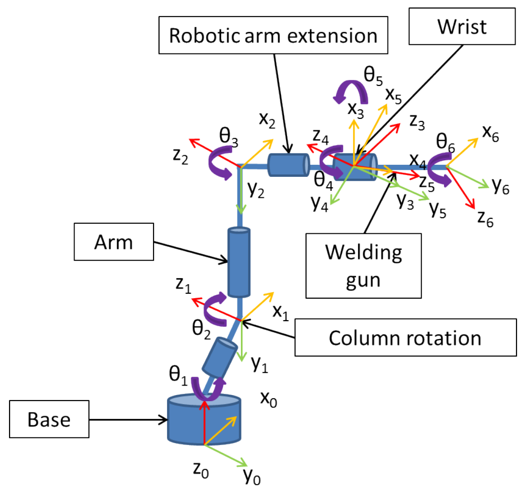

FIGURE 2. **Manipulator robot selected.**

trajectories in the automotive sector. In this sector, the main input in the design of a productive cell is the cycle time and therefore the numbers of units produced per hour. This method applied in serial manipulators guarantees that the robots joints are kept away from possible singularities and reducing the effort supported by each of the joints. In addition, this trajectory optimization will be analyzed from an economic perspective, as it offers considerable economic potential.

II. FLOWCHART OF THE OPTIMIZATION OF ROBOT TRAJECTORIES

The flowchart in Fig. 1 represents the sequence followed for optimizing any trajectory in any manipulator. It corresponds to a software created for this purpose in which the robot and the trajectory selected as inputs must be used to optimize the manipulability and the trajectory itself. First, the defined kinematics of the manipulator chosen must be investigated to be able to implement the objective function in [3] and [5]. This function will be implemented until the criterion of defined unemployment in [3] and [5] is met. Once this process is completed, the software yields the new values of manipulability and the optimized trajectory.

III. STUDY OF THE KINEMATICS OF A ROBOT WITH SIX DOFS AND A SPHERICAL WRIST

Given that the majority of industrial robots in the automotive industry are serial manipulators of six DOFs and a spherical wrist, this study considers and applies the Kalman algorithm to this type of robot. For this simulation, the robot KUKA KR16 HW, which is a robot that is used to couple a final effector for welding with an electric arc and shielding gas, is used. The components and movements of the robot are shown in Fig. 2, and its kinematic model is shown in Table 1.

First, the kinematics of this manipulator must be considered. In this manipulator, the number of DOFs refers to the number of independent variables that exist. In industrial serial manipulators, the position of every articulation is defined with a single variable. Therefore, the number or articulations of the manipulator makes it is equal to the number of DOFs.

A. DIRECT KINEMATICS OF THE SERIAL MANIPULATOR WITH SIX DOFS AND A SPHERICAL WRIST

Direct kinematics refers to the position and orientation of the end of the manipulator (tool or final effector) with regard to its base. It is also used to determine the geometrical parameters of the arm. The convention most used to suggest the relations between links of the manipulator is the convention of Denativ–Hartenberg (DH). Using this method, the variables of the kinematic model are identified. This method is the starting point in this paper.

From this kinematic model, the matrices of homogeneous transformation are found for each of the articulations. With these matrices of homogeneous transformation, the position

TABLE 1. Kinematic model for the DH of a robot with six DOFs and a spherical wrist, modified from [27].

Articulation (θ_i)	di (m)	a_i (m)	α_i (degrees)
θ_1	d_1	a_1	-90
θ_2	0	a_2	0
θ_3	d_3	a_3	-90
θ_4	d_4	0	90
θ_5	0	0	-90
θ_6	$d_6 + d_h$	a_h	0

where:
a_i is the distance measured between z_i and z_{i+1} measured by x_i
α_i is the angle measured between z_i and z_{i+1} measured by x_i
d_i is the distance measured between x_{i-1} and x_i measured by z_i
θ_i is the angle measured between x_{i-1} and x_i measured by z_i

and orientation of the tool fitted to the robot can be obtained as

$$ {}^{0}_{6}T = {}^{0}_{1}A \times {}^{1}_{2}A \times {}^{2}_{3}A \times {}^{3}_{4}A \times {}^{4}_{5}A \times {}^{5}_{6}A \tag{1} $$

where
T is the matrix of position and orientation of the tool
${}^{x}_{x+i}A$ is the matrix of homogeneous transformation of the articulation x + i

B. INVERSE KINEMATICS OF THE SERIAL MANIPULATOR WITH SIX DOFS AND A SPHERICAL WRIST

In the next step, the Kalman algorithm is applied to find the inverse kinematics of the manipulator. Inverse kinematics refers to the position and orientation of the end of the tool fitted to the robot (in this case, the welding gun). The articular variables are obtained to position and orient the tool in a specific position in space.

In this case, the inverse kinematics have been solved by geometrical methods [23]. This technique is an ideal method for studying robots that only consider the first DOF, which are responsible for positioning the end. Through geometrical methods, the variables were studied to determine the position of the first three articulations of the robot.

As the wrist robot under consideration is a manipulator with six DOFs and a spherical wrist, one-disconnect kinematics can be performed [23]. This one-disconnect consists of dividing the inverse kinematics of the robot into two independent problems: one to find the intersection of the axes in the wrist and another for determining the orientation of the wrist.

The use of these two steps is because in manipulators with spherical wrists, the movement of the three last links does not change the position of the center of the manipulator's wrist.

When calculating the inverse kinematics, the orientation and position of the end of the tool with regard to the base of the robot is known. Hence,

$$ P.wrist_4^0 = {}_6^0T \times P.wrist_4^6 \tag{2} $$

where
P. $wris_4^0$ is the position of the wrist compared to the base of the robot
P. $wrist_4^6$ is the position of the end of the tool compared to the wrist
Consequently, considering the specifications of the robot under consideration yields

$$ P.wrist_4^0 = \begin{pmatrix} r_{11} & r_{12} & r_{13} & p_x^0 \\ r_{21} & r_{22} & r_{23} & p_y^0 \\ r_{31} & r_{32} & r_{33} & p_z^0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 0 \\ 0 \\ L_{wrist} \\ 1 \end{pmatrix} \tag{3} $$

where
r_{ij} is the position of the articulation i respect to the articulation j
L_{wrist} is the wrist length
p_i^0 is the position on the axis (i = x, y or z) of the tool
Solving and applying geometrical methods yields

$$ \theta_1 = \arctan 2(p.wristy_4^0, p.wristx_4^0) \tag{4} $$
$$ \theta_2 = \alpha_2 + \gamma_2 \tag{5} $$
$$ \theta_3 = 90 - (\alpha_3 + \gamma_3) \tag{6} $$
$$ \theta_4 = \arccos(-r_{31}/\sqrt{1 - r_{33}^2}) \tag{7} $$
$$ \theta_5 = \arccos(r_{33}) - \pi \tag{8} $$
$$ \theta_6 = \arccos(r_{31}/\sqrt{1 - r_{33}^2}) \tag{9} $$

where γ_2 is the angle formed by the horizontal and the segment that joins the articulation 2 with the center of the wrist and γ_3 is the angle formed by a_2 and the segment that joins the articulation 3 with the center of the wrist.

C. DIFFERENTIAL KINEMATICS OF A SERIAL MANIPULATOR WITH SIX DOFS AND A SPHERICAL WRIST

Once the direct and inverse kinematics of the manipulator are known, the Jacobian matrix must be used before studying the manipulability on the selected manipulator.

The Jacobian matrix of the manipulator relates the articular speeds to the Cartesian speeds of its extremities. By employing the disconnect kinematic suggested beforehand, the differential kinematics will be treated with regard to the center of the wrist and will be the preliminary point of the differential kinematics.

$$ V_w = \begin{bmatrix} w_w \\ \dot{p_w} \end{bmatrix} = J(\theta) \times \dot{\theta} \tag{10} $$

where
w_w is the angular speed of the wrist
p_w is the linear speed of the wrist

$$ V_w = \left[v_x v_x v_x \theta_x \theta_y \theta_z\right]^T = \begin{pmatrix} w_w \\ \dot{p_w} \end{pmatrix} \tag{11} $$

Using the Jacobian matrix yields

$$ J = \begin{bmatrix} J_{ra} & J_{rw} \\ J_{ta} & 0 \end{bmatrix} \tag{12} $$

where

J_{ra} is the Jacobian matrix of the rotational part of the arm

J_{rw} is the Jacobian matrix of the rotational part of the wrist

J_{ta} is the Jacobian matrix of the translational part of the arm

$$w_m = J_{ra} \times \dot{\theta}_a + J_{rw} \times \dot{\theta_w}; \dot{\theta}_w = J_{rw}^{-1} \times (w_w - J_{ra} \times \dot{\theta}_a) \tag{13}$$

$$\dot{p}_w = J_{ta} \times \dot{\theta}_a; \dot{\theta}_a = J_{ta}^{-1} \times \dot{p}_w \tag{14}$$

Analogously, for the case of accelerations, the sub-parts of the arm and wrist would remain as

$$\ddot{\theta}_w = J_{rw}^{-1} \times (w_w - J_{ra} \times \dot{\theta}_a - J_{ra} \times \ddot{\theta}_a - J_{rw} \times \dot{\theta}_w) \tag{15}$$

$$\ddot{\theta}_a = J_{ta}^{-1} \times (\ddot{p}_w - J_{ta} \times \dot{\theta}_a) \tag{16}$$

D. SOLVING THE MANIPULABILITY IN A SERIAL MANIPULATOR WITH SIX DOFS AND A SPHERICAL WRIST

Once all kinematic parameters of the manipulator are known, the manipulability can be calculated, which is the main goal of this article.

Based on suggestions made by Yoshikawa [24], the index of manipulability is known as the final factor in changing the position and orientation. Yoshikawa suggested that manipulability can be seen as an ellipsoid in the Euclidean space geometry; thus, for the manipulator with six DOFs and a spherical wrist under consideration, we have the following inequality:

$$\sqrt{\dot{q}_1^2(t) + \dot{q}_2^2(t) + \dot{q}_3^2(t) + \dot{q}_4^2(t) + \dot{q}_5^2(t) + \dot{q}_6^2(t)} \leq 1 \tag{17}$$

where

$\dot{q}_n$ represents the articular speeds of each of the articulations of the robot system.

As has been described beforehand, the relation between the articular speed and the Cartesian speed is given by the Jacobian matrix. Consequently, the index of manipulability is defined as

$$w = \det \sqrt{J(q) \times J^T(q)} \tag{18}$$

Similarly, and based on [25], we can define the manipulability of a manipulator with six DOFs and a spherical wrist as the product of the manipulability of the sub-part of the arm and that of the wrist, that is,

$$w = w_a \times w_w \tag{19}$$

E. METHOD OF OPTIMIZATION: KALMAN ALGORITHM

As has been mentioned previously, the method of Kalman [19] will be used to optimize the manipulability and thus be able to validate the optimal search method. For the implementation of this method use a normal probability density function, and a Kalman estimator [26]. This will be applied to a serial robot manipulator with robot with six DOFs and a spherical wrist.

The proposed procedure is iterative in that first there is a random generator of probability functions which produce a collection of N vectors distributed thorough a variance-covariance matrix $\Sigma(j)$ and a vector of averages $m(j)$ so that it has to:

$$k(j) = \{k^1(j)\, k^2(j), \ldots k^N(j) \tag{20}$$

where

$K^i(j)$ is the i-th vector that is generated in the iteration k.

This random generator is applied to the cost function so that described algorithm change the vector of averages and the matrix of variances of the generator until a solution of the desired quality.

A measurement process followed by an estimator is introduced to achieve a desirable estimation of the optimum. So the candidates that best represent the optimum is averaged. So it should be:

$$\xi(j) = \frac{1}{N_\xi} \sum_{i=1}^{N_\xi} k^i(j) \tag{21}$$

where

N_ξ is the number of the best examples to consider.

The measure will come given by:

$$\xi(j) = k_{optimo} + \upsilon(j) \tag{22}$$

where

$\upsilon(j)$ is an unknown disturbance.

This uncertainty is estimated taking into account the information available, i.e. the best samples.

The lack of the knowledge of the optimum is taken account using the vector of variance associated with the best samples. Therefore it should be:

$$\upsilon(j) = \frac{1}{N_\xi} \left[\sum_{i=1}^{N_\xi} \left(k_1^i(j) - \xi_1(j) \right), \ldots, \sum_{i=1}^{N_\xi} \left(k_{n_j}^i(j) - \xi_{n_j}(j) \right) \right]^T \tag{23}$$

In such conditions a Kalman estimator can be used to perform the estimated. Taking as a basis the Kalman equations [19], the rule to update the Gaussian generator would be:

$$m(j+1) = m(j) + P(j)(\xi(j) - m(j)) \tag{24}$$

$$\sum(j+1) = (I - b(j) * P(j)) * \sum(j) \tag{25}$$

where

$d(j)$ is a diagonal matrix with diagonal corresponding to the vector of variance υ(j).

$b(j)$ is a coefficient used to decreased the time of variance matrix $\sum$(j).

To initialize and adjust the parameters of the Gaussian generator, it should cover the full space search space. For this reason:

$$m_0 = \begin{bmatrix} \mu_1 \\ \vdots \\ \mu_{nk} \end{bmatrix}, \quad \sum\nolimits_0 = \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \sigma_{nk} \end{bmatrix} \tag{26}$$

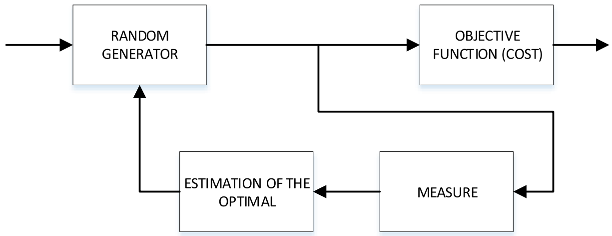

FIGURE 3. Implementation of the Kalman algorithm.

where

$$\mu_i = \frac{k_{i\,\sup} + k_{i\ inf}}{2}, \quad para\ i = 1, ..n_k \tag{27}$$

$$\sigma_i = \frac{k_{i\,\sup} + k_{i\ inf}}{6}, \quad para\ i = 1, ..n_k \tag{28}$$

As has been mentioned previously, an estimator of Kalman [26] will be used to optimize the manipulability and will be applied to a serial robot manipulator with six DOFs and a spherical wrist. As is known, this estimator is based on a measurement model divided into two stages: a first stage that consists of the measurement of the state, position and orientation of the final effector itself and a second stage in which the correction is carried out and updated for the future state.

This Kalman algorithm is used to maximize the manipulability of the trajectory, taking the variables of the working space of the robot as a base. Then, the goal function cost is defined to be minimized, i.e., it is composed of the maximization of the manipulability (Fig. 3):

$$Q(q) = \sum\nolimits_{n=1}^{N} max(R_i\,(q)\,,0) \tag{29}$$

where

N is the number of restrictions imposed (limits of the robot and articular speeds)

$R_i\,(q)$ is the function of the i-th restriction

In addition, the criteria of unemployment of the algorithm are set to occur when 15 iterations are carried out and when the deviation in the absolute value between the current iteration and the previous one is smaller than 0.001.

IV. CASE STUDY: SERIAL ROBOT

The family KUKA KR is a family of industrial robots with six axes and a union of kinematic arm that enables the control of points and of trajectories with high accuracy. The object variant of study, the robot KUKA KR 16 HW, has an arm and an articulation of hollow axis (Hollow Wrist, HW), through which the tubes of the welding gun are driven.

A. ROBOT CHARACTERISTICS

The technical characteristics of the robot are now presented. We consider the working space in which the robot is capable of acting (Fig. 4) and provide a description of its basic characteristics and the position and allowed speed of each of its shafts (Table 2).

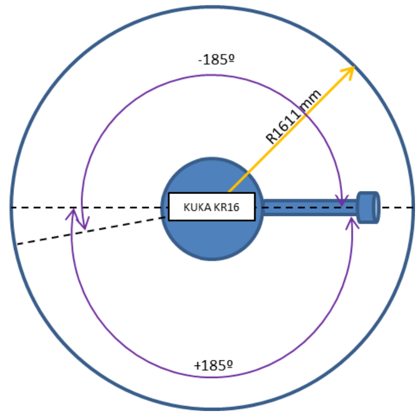

FIGURE 4. Working space of the robot, modified from [27].

TABLE 2. Position and speed of each axis of the robot [modified from 27].

Robot axis	Position [º]	Speed [º/s]
1	±185	192
2	-35 / -155	173
3	-154 / -130	192
4	±350	329
5	±130	332
6	±350	789

The characteristics of the tool fitted in its end that welds through material contribution is also considered.

Similarly, and according to the calculation of the kinematic parameters, the position and speed of each axis of the robot are defined in Table 2.

The tool that is fitted to the robot to carry out the welding process through an electric arc is the robotic gun of MIG Tough Gun CA3. This tool uses air refrigeration. This welding gun has been chosen because it is one of the typical guns used in industrial processes that require automated welding. It provides considerable accuracy and is easy to maintain. Moreover, a neck configuration of 45 degrees and 400 linear mm is chosen.

B. TRAJECTORIES

To evaluate the behavior of the proposed optimization algorithm, two different trajectories of welding are considered. These two trajectories have been obtained from two real trajectories that must be studied. Both trajectories correspond to the manufacture and assembly of the body of a vehicle.

The first trajectory, called Trajectory 1, consists of 95 program points of the robot and corresponds to welding inside the right part of the dashboard of the vehicle (see Fig. 5).

The second trajectory, called Trajectory 2, consists of 84 program points of the robot and corresponds to welding in the vehicle floor (see Fig. 6).

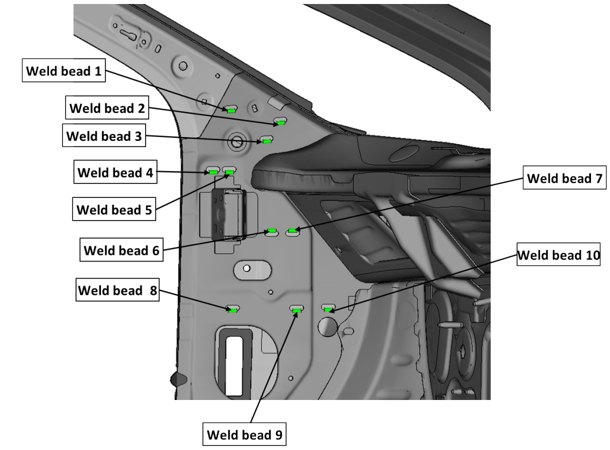

FIGURE 5. Trajectories of welding Trajectory 1.

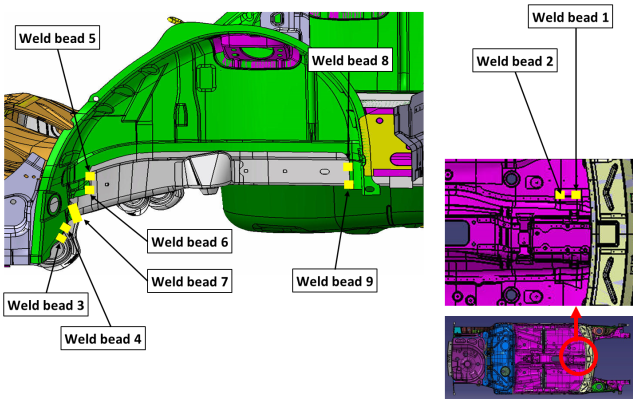

FIGURE 6. Trajectories of welding Trajectory 2.

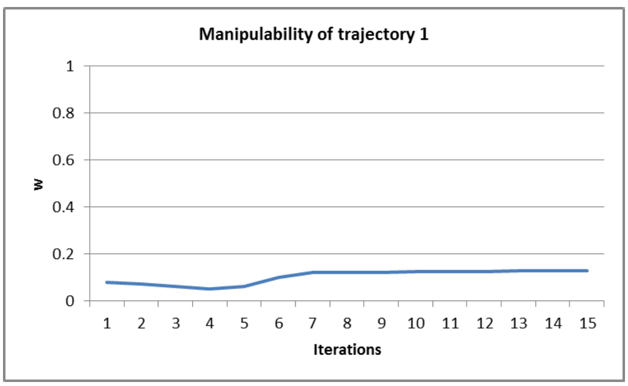

FIGURE 7. Average manipulability for the trajectories of welding Trajectory 1.

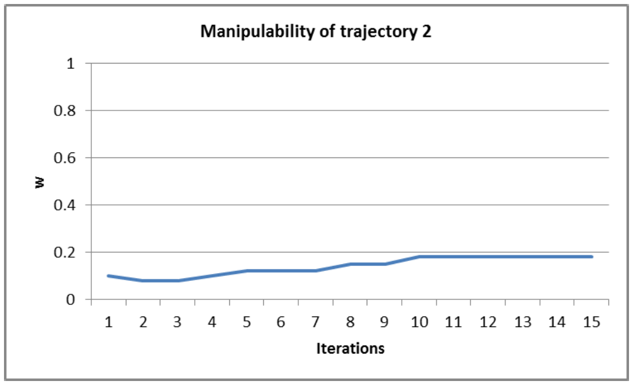

FIGURE 8. Average manipulability for the trajectories of welding Trajectory 2.

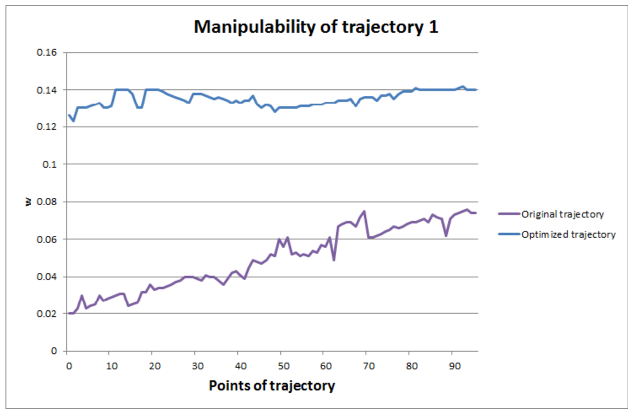

FIGURE 9. Original manipulability and optimization for the trajectories of welding Trajectory 1.

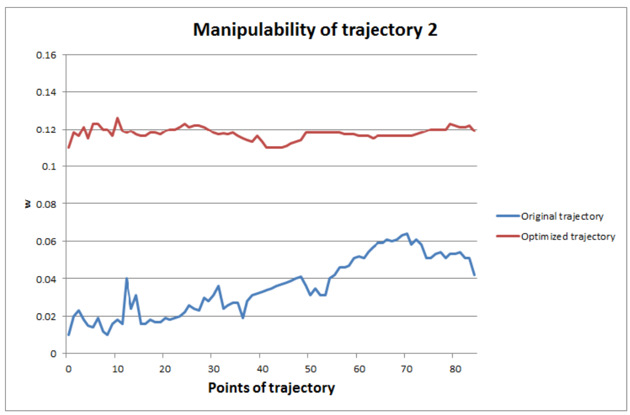

FIGURE 10. Original manipulability and optimization for the trajectories of welding Trajectory 2.

C. OBTAINED RESULTS

In this sub-part, the results obtained for the optimization algorithm for both trajectories with the robot and welding gun are presented.

In Fig. 7 and Fig. 8, the behavior of the manipulability is observed as the algorithm keeps optimizing the trajectories of welding Trajectory 1 and Trajectory 2. As mentioned in the explanation of the algorithm, the algorithm will stop at iteration 15 as long as the rule of unemployment is observed.

In both graphs, the stop criteria are met at iteration 15. This result illustrates that the vector of averages and of variances of the algorithm must be initialized to prevent the algorithm from converging to a local solution due to the inverse kinematics of the manipulator.

TABLE 3. Percentages of the optimization of trajectories of welding Trajectory 1 and Trajectory 2.

		Trajectory 1	Trajectory 2
Original trajectory	Points of trajectory	95	84
	Time of trajectory	73.6 s	81.4 s
	w average	0.05	0.0357
Optimized trajectory	Iteration	15	15
	Time of trajectory	70.1 s	78.5 s
	w average	0.1352	0.1175
Percentage Optimized w		63.01%	69.61%

TABLE 4. Economic savings with the implementation of the algorithm.

		Trajectory 1	Trajectory 2
Trajectory time (seconds)	Initial trajectory	73.6	81.4
	Optimized trajectory	70.1	78.5
	Δt	3.5	2.9
Production / day (cars)	Initial trajectory	1043	943
	Optimized trajectory	1095	978
	Δp	52	34
Economic saving (€)		24648	16116

As observed in Fig. 7 and Fig. 8, the factor of manipulability tends to stabilize and be a constant, which is the condition that we wish to achieve over multiple iterations.

Fig. 9 and Fig. 10 show that the manipulability in the trajectory optimized throughout the different points of the trajectory is generally larger and tends to be more constant than in the original trajectory in both trajectories.

As shown in Table 3, the own time of trajectory decreases with the optimization of the manipulability. Therefore, this optimization process can be applied to an industrial series process to reduce costs. The economic savings resulting from the application of this optimization as it passes the daily production of vehicles in body shop are noted, including those stations in which these welding joints are used, and the values are shown in Table 4.

V. CONCLUSIONS

This paper presented an optimization algorithm based on the Kalman filter. This filter predicts future states under a given uncertainty. The Kalman filter runs in real time using measurements and current states calculated together with the uncertainty matrix. This filter was used to optimize the manipulability in a manipulator with six DOFs and with a spherical wrist that performs arc welding.

The method was validated with simulations of displacements in the different points of the trajectory and including the kinematic parameters of the manipulator itself. Therefore, this method allows calculations to be performed from any trajectory given in Cartesian coordinates and directions of the final effector end, provides optimized solutions of trajectory/manipulability that always preserve the orientation of the tool, and gives basic orientations for correct welding in the union method of arc welding.

The obtained results demonstrate that the proposed algorithm is an appropriate method for optimizing trajectories. This method has various advantages, such as ease of implementation and that the states of calculation are based only on previous states. However, this approach presents an inconvenience in that it can converge to local solutions. Consequently, the algorithm must be initialized correctly

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