

Development of tele-operation control for a free-floating robot during the grasping of a tumbling target

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Abstract

This paper addresses the singularities avoidance problem while performing a grasping maneuver in tele-operation with a manipulator mounted on a free-floating spacecraft. Firstly, the independence of the singularities of the end-effector Jacobian of a generic free-floating system from the inertial parameters of the last link is demonstrated. Secondly, the possibility to represent all the singularities in the Cartesian space for a free-floating system provided with three reaction wheels is shown. Finally an optimization algorithm is presented, which provides the optimal spacecraft initial Cartesian position and attitude, to allow the operator to keep a trajectory in the vicinity of the nominal motion while satisfying operational constraints as long as possible.

1 Introduction

When a target travels along a certain trajectory, the ability to precisely track its Cartesian position and orientation with the manipulator end-effector by the human operator is essential to limit the forces developed at the grasp. If however, during this time, the end-effector moves in the vicinity of a singular configuration, the manipulator Jacobian matrix is ill-conditioned and instantaneously, the desired end-effector movement may not be achieved. As a consequence, the relative velocity between the end-effector and the target is not null and an impact occurs at the grasp. Furthermore the necessity to exactly keep a certain trajectory is justified when considering that the large target angular momentum, if its mass is very similar to that of the chaser, could develop great forces during impact. Even if the redundancy might be exploited to keep the manipulator far from singular configurations, the impossibility to allow, in space applications, high joints rates, gives rise to similar trajectory maintenance difficulties. As such problems especially occur in the vicinity of the singularities, these regions should primarily be avoided.

In order to overcome this problem the human operator should know the position of all the singularities

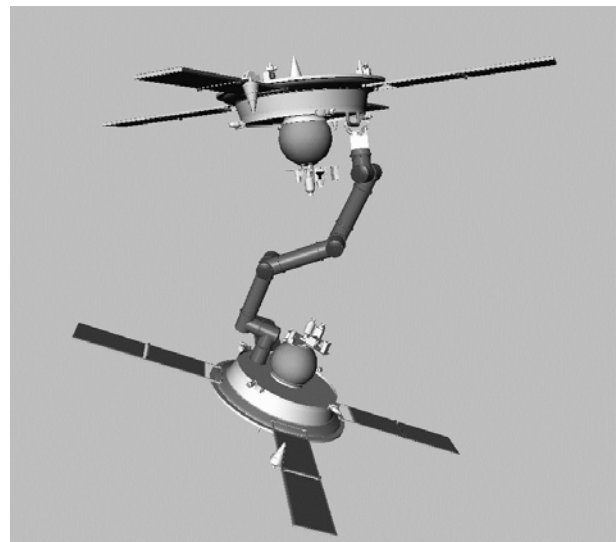


Figure 1 Tecsas free-floating system

of the manipulator. Unfortunately it is very difficult to provide intuitive singularities representation because the singular configurations are defined in joint space R^n , and in general they cannot be represented in 3D Cartesian space.

Several approaches have been developed to handle the singularity problem. Resorting to an explicit deviation from the desired trajectory, G. Schreiber, M. Otter and G. Hirzinger developed in [2], for a non redundant manipulator, a kinematic solution method allowing a Cartesian error in a given subspace in the vicinity of a singularity and minimizing this error. S. Dubowsky and E. Papadopoulos analyze in [1] the singularities path dependence. They found some region in the inertial workspace, called the Path Independent Workspace (PIW), where dynamic singularities will not exist for any path taken within this region. C. R. Carignan and D. L. Akin illustrate in [7] the benefits of autonomous spacecraft attitude stabilization through reaction moment compensation. Finally J. R. Spofford and D. L. Akin develop in [3] inverse kinematics for a redundant free-flying robot allowing for singularity avoidance. The inverse kinematics is solved by formulating a potential function optimization problem

and exploiting the right pseudo-inverse Jacobian matrix and the manipulability function.

In this paper the problem of docking to a tumbling target satellite in teleoperation, using a free-floating space system, is addressed. The manipulator end-effector is required to follow without deviation a point fixed to the target, also keeping a certain orientation relative to it. Particular attention is given to the singularity avoidance, by resorting to the manipulability potential, to the collision avoidance between the target and the chaser satellite as well as to the joint coordinate and rate limits. Although the ratio between the masses of the robot and of the base is high ($\approx 1/7$), no base-platform stabilization is needed during arm operations. The inverse kinematics used in [3] will here be applied to the "Tecas" 7 DOF manipulator (see figure 1). In section two the inverse kinematics adopted will be briefly explained. In section three the independence of the manipulator singularities from the inertial properties of the end-effector and from the last joint coordinate will be demonstrated and the implications will be shown. In section four an algorithm able to represent the singular manipulator regions for a free-floating system provided with reaction wheels, will be described. Even if the Tecas system does not have any reaction wheels, this method will be applied to it and the results shown. Finally in section five the inverse kinematics, shown in section two, will be exploited to develop an algorithm to provide the optimal initial configuration of the robot, which allows the operator to satisfy certain manipulator constraints as long as possible.

2 Inverse kinematics

Let us consider an n-DOF manipulator. \mathbf{v}_E is the end-effector generalized 6x1 velocity vector and \mathbf{q} the nx1 joint coordinates vector. As described in [4] pp. 29-39 a 6xn Jacobian matrix \mathbf{J}_E can be written for a floating system so that:

$$\mathbf{v}_E = \mathbf{J}_E \dot{\mathbf{q}} \quad (1)$$

The problem is to find the \mathbf{q} derivative vector that satisfies equation (1). As the manipulator is redundant, the \mathbf{J}_E matrix is not square ($n=7$) and it cannot be inverted. Hence the traditional approach, as described in [5] par.3.6, is to use the pseudo-inverse nx6 matrix defined as:

$$\mathbf{J}^\dagger = \mathbf{J}_E^T (\mathbf{J}_E \mathbf{J}_E^T)^{-1} \quad (2)$$

The \mathbf{J}^\dagger matrix has rank=6, therefore it has a null space of dimension n-6. By resorting to the matrix $(\mathbf{E}_{n \times n} - \mathbf{J}^\dagger \mathbf{J}_E)$, projecting a generic nx1 $\boldsymbol{\varphi}$ vector in the \mathbf{J}_E null space, the most general solution of equation (1) is:

$$\dot{\mathbf{q}} = \mathbf{J}^\dagger \mathbf{v}_E + (\mathbf{E}_{n \times n} - \mathbf{J}^\dagger \mathbf{J}_E) \boldsymbol{\varphi} \quad (3)$$

where $\mathbf{E}_{n \times n}$ is the nxn identity matrix. The end-effector velocity is not modified by the $\boldsymbol{\varphi}$ vector. A typical choice of $\boldsymbol{\varphi}$ is:

$$\boldsymbol{\varphi} = \sum_i k_i \left(\frac{\partial \omega_i(\mathbf{q})}{\partial \mathbf{q}} \right)^T \quad (4)$$

where $k_i > 0$ and $\omega_i(\mathbf{q})$ is a (secondary) objective function dependent on the joint variables. Since the gradient has been used $\boldsymbol{\varphi}$ attempts to locally maximize ω . As we want to guarantee the singularity avoidance, the collision avoidance between the target and the chaser satellite and the joint coordinate limits, the following objective functions have been chosen:

1. Manipulability measure

$$m(\mathbf{q}) = \sqrt{\det(\mathbf{J}_E \mathbf{J}_E^T)} \quad (5)$$

2. Distance from mechanical joint limit

$$l(\mathbf{q}) = -\frac{1}{2n} \sum_{i=1}^n \left(\frac{q_i - \bar{q}_i}{q_{iM} - q_{im}} \right)^2 \quad (6)$$

where q_{iM} (q_{im}) is the maximum (minimum) joint limit, \bar{q}_i is the middle value of the joint range.

3. Distance between the two satellites.

It is worth pointing out that the distance function is not only a function of \mathbf{q} , depending also on the spacecraft attitude and therefore, being a floating system, on the path taken in joint space. As it cannot be seen as a potential function, the solution is only locally optimal and better solutions might exist for large maneuvers. However, the results also show that this function provides a local optimization of the distance between the two satellites, justifying its use.

3 Last link singularities mass dependence

As the grasping operation is completed, the manipulator/chaser satellite system changes since a new body becomes part of it. If there is no relative motion between the target satellite and the manipulator end-effector, the new system differs from the old one only for the mass, center of mass position and moment of inertia of the end-effector. The new end-effector inertial properties depend on those of the manipulator end-effector and those of the target satellite. In the present section the independence of the generic manipulator singularities from all the inertia properties of the end-effector and from the last joint coordinate will be demonstrated. The above consideration leads to the conclusion that the singular regions do not change as a target is docked.

First it is worth observing that the singularities do not change within the same rigid body. If \mathbf{p}_1 and \mathbf{p}_2 are two points of the end-effector link and \mathbf{J}_1 and \mathbf{J}_2 their relative Jacobians, the relationship between the two matrixes is:

$$\mathbf{J}_1 = \begin{pmatrix} \mathbf{E} & -\mathbf{S}(\mathbf{p}_2 \mathbf{p}_1) \\ \mathbf{0} & \mathbf{E} \end{pmatrix} \mathbf{J}_2 \quad (7)$$

where \mathbf{E} is the 3x3 identity matrix and $\mathbf{S}(\mathbf{x})$ is the skew-symmetric matrix describing the vector product between

\mathbf{x} and another 3×1 vector as $\mathbf{x} \times \mathbf{y} = \mathbf{S}(\mathbf{x})\mathbf{y}$. The 6×6 matrix relating the Jacobians is always invertible. Hence \mathbf{J}_1 and \mathbf{J}_2 have the same rank.

As described in [4], section 3, the following relation can be written between the generalized 6×1 spacecraft velocity vector \mathbf{v}_B and the joint rates vector:

$$\mathbf{F}\mathbf{v}_B = -\mathbf{G}\dot{\mathbf{q}} \quad (8)$$

where

$$\mathbf{F} = \begin{pmatrix} m_{\text{sys}}\mathbf{E} & m_{\text{sys}}\tilde{\mathbf{r}}_0 \\ \mathbf{0} & \mathbf{I}_{\text{sys}} \end{pmatrix} \quad (9)$$

m_{sys} and \mathbf{I}_{sys} being the system total mass and inertia moments matrix respectively and $\tilde{\mathbf{r}}_0$ the skew matrix of the base center of mass position with respect to the system center of mass. \mathbf{G} is a matrix depending only on the links inertial properties but not on those of the spacecraft. $-\mathbf{F}^{-1}\mathbf{G}$ is the spacecraft Jacobian. It is easy to verify that \mathbf{F} is always an invertible matrix. Hence the spacecraft Jacobian singularities depend only on \mathbf{G} . Therefore they do not depend on the spacecraft inertial properties. As it is possible to mentally exchange the end-effector and spacecraft rules, by considering the end-effector a “new” spacecraft and vice versa, it follows that the “old” end-effector singularities do not depend on its own inertial properties. Furthermore as the singularities do not change within the same link, a point on its axis can be chosen to evaluate the Jacobian for the singularities computation. Since its position and the last axes orientation do not depend on the last joint coordinate and since the singularities do not depend on the last link inertial properties, it follows that the singularities do not depend on the last joint coordinate.

4 Floating robot provided with reaction wheel

4.1 Generalities on the singularities representation

A good idea while performing a teleoperation maneuver with a robotic system would be to provide the operator with a representation of the manipulator singularities in the 3D Cartesian space. For e.g. if the end-effector was going through certain Cartesian regions a singularity would occur. Such a representation would let the operator handle by himself the singularity avoidance problem. It is worth pointing out that such a representation not only lets the operator know whether the manipulator configuration is instantaneously singular (as the manipulator ellipsoids could do), but it always gives the operator the information of where the singular regions are. The operator can understand at a glance whether, performing a particular manoeuvre, the manipulator might reach a singularity. It is worth underlining that such information towards the singularities is the most complete and useful information the operator might have. Such a representation might definitely solve the problem of the manipulator singularities feed-back to the operator, greatly

improving the effectiveness of the manipulator teleoperation control.

As already discussed in the introduction, the impossibility to allow, in space applications, high joints rates, gives rise to trajectory maintenance difficulties similar to those of the singularities. The impossibility to keep the correct trajectory, coming from low joints rates, arises in much more configurations than those which are singular, strongly depending on the end-effector desired velocities. However, as such problems especially occur in the vicinity of the singularities, these regions should primarily be avoided.

Unfortunately problems occur when trying to provide a 3D space representation of the singularities, because they would probably fill the whole manipulator workspace. A very simple example can demonstrate it. Let us consider a fixed-based 6 DOF robot. If the robot has a wrist with the three joint axes intersecting in a point a well-known singularity condition is when the second wrist joint coordinate is null. Since the linear position only depends on the arm degrees of freedom, a Cartesian point can be reached with all the orientations, these depending only on the wrist configuration. In this way every Cartesian point can be reached with a null second wrist joint coordinate and as a result, all the Cartesian end-effector workspace points would be singular. This example suggests that the problem to represent a R^n information ($n > 3$) in a R^3 space might not be possible.

It will be demonstrated that for a free-floating robot with reaction wheels a representation of the singularities could be given.

4.2 Equations of a manipulator/spacecraft system with reaction wheels

Let us consider an n -link free-floating robot with 3 reaction wheels, whose axes unit vectors do not lie on the same plane, mounted on the base. Three DOF have been added to the system. Furthermore, being the axes unit vectors always linearly independent, they are not expected to give rise to singular configurations. By exploiting these DOF to command the manipulator end-effector, the rank of the new $6 \times (n+3)$ Jacobian matrix is expected to always be higher than three.

The new Jacobian matrix has been derived in [8] for a system with every reaction wheel center of mass lying on its rotation axis, which is also supposed to be a principal axis of inertia. With such an assumption a very expressive Jacobian form can be derived by computing the new Jacobian matrix \mathbf{J}^* for the point in the frame attached to the end-effector that instantaneously coincides with the system center of mass \mathbf{C}_M . It is worth pointing out that this point does not physically belong to the end-effector and that it is always moving in the end-effector reference frame. To derive the Jacobian for a generic point \mathbf{P} of the end-effector the following matrix multiplication is required:

$$\mathbf{J}_P = \begin{pmatrix} \mathbf{E} & -\mathbf{S}(\mathbf{C}_M\mathbf{P}) \\ \mathbf{0} & \mathbf{E} \end{pmatrix} \mathbf{J}^*$$

The $6 \times (n+3)$ \mathbf{J}^* matrix is:

$$\mathbf{J}^* = \begin{pmatrix} \mathbf{J}_{\text{CM}}^{\text{LIN}} & \mathbf{0} \\ \mathbf{J}_{\text{CM}}^{\text{ANG}} & \mathbf{J}_{\text{wheel}} \end{pmatrix}$$

where $\mathbf{J}_{\text{CM}}^{\text{L}}$ and $\mathbf{J}_{\text{CM}}^{\text{A}}$ are the linear and angular parts, respectively, of the 6xn Jacobian matrix computed for the above mentioned point, for a system without reaction wheels and $\mathbf{J}_{\text{wheel}}$ is:

$$\mathbf{J}_{\text{wheel}} = \mathbf{I}_{\text{TOT}}^{\text{CM}}^{-1} \begin{pmatrix} {}^1I_{1zz} \mathbf{z}_1 & {}^2I_{2zz} \mathbf{z}_2 & {}^3I_{3zz} \mathbf{z}_3 \end{pmatrix}$$

where $\mathbf{I}_{\text{TOT}}^{\text{CM}}$ is the inertia matrix of the system computed with respect to the system center of mass \mathbf{C}_{M} , \mathbf{z}_i is the axis unit vector of the i^{th} reaction wheel and ${}^iI_{izz}$ is the axis inertia moment of the i^{th} reaction wheel computed with respect to its own center of mass and expressed in its own reference frame.

Being the axes unit vectors always linearly independent, the $\mathbf{J}_{\text{wheel}}$ matrix is always invertible and therefore $\text{rank}(\mathbf{J}^*) \geq 3$. In every configuration all angular velocities can be obtained. It follows that only the linear velocity singularities must be analyzed.

4.3 Algorithm to compute the singularities of a manipulator/spacecraft system with reaction wheels

In the present section an algorithm to compute the \mathbf{J}^* singularities will be presented and the possibility to represent them in a 3D Cartesian space will be demonstrated. For more details please see [8].

The singularities search needs a detailed analysis of the Jacobian matrix form. Hence the expression for the $\mathbf{J}_{\text{CM}}^{\text{L}}$ generic j^{th} -column has been found:

$$\mathbf{J}_{\text{CM}}^{\text{LIN}} \Big|_j = - \frac{m_{j-1}^* \mathbf{S}(\mathbf{P}_{j-1} \mathbf{C}_{j-1}^*)}{m_{\text{TOT}}} \mathbf{z}_{j-1} \quad (10)$$

where \mathbf{P}_{j-1} is a generic point on the j^{th} joint, \mathbf{z}_{j-1} is the $j-1^{\text{th}}$ axis unit vector, m_{TOT} is the total mass and

$$m_{j-1}^* = \sum_{i=0}^{j-1} m_i$$

$$\mathbf{C}_{j-1}^* = \frac{\sum_{i=0}^{j-1} m_i \mathbf{C}_i}{m_{j-1}^*}$$

where m_0 is the mass of the spacecraft plus that of the reaction wheels and \mathbf{C}_i is the i^{th} center of mass. The most important consequence of this expression is that every column depends on $q_1 \dots q_{j-1}$. Furthermore the $m_{\text{TOT}}^* \mathbf{J}_{\text{CM}}^{\text{L}}$ matrix rank problem can be worked out. In fact the multiplication by a scalar quantity does not change the rank of a matrix. This matrix will be called \mathbf{L} .

To begin the analysis a reference frame must be chosen. If \mathbf{B} is the center of mass of the system composed by the base and the three wheels, the chosen origin lies on the intersection between the first joint axis

and the minimum distance with the point \mathbf{B} straight line. Let the \mathbf{z}_0 unit vector have the first joint axis direction and the \mathbf{x}_0 unit vector have the minimum distance straight line direction. The \mathbf{y}_0 unit vector is obtained in the right hand sense. With such a choice the \mathbf{L} matrix is:

$$\mathbf{L} = \begin{pmatrix} 0 & L_{12} & L_{13} & \dots & L_{1n} \\ m_0 a_0 & * & * & \dots & * \\ 0 & L_{32} & L_{33} & \dots & L_{3n} \end{pmatrix}$$

where a_0 is the distance between \mathbf{B} and the first joint axis. Let us suppose that a_0 is not null. Then the singular configurations are determined by the solution of the equation system:

$$\det \begin{pmatrix} L_{1i} & L_{1j} \\ L_{3i} & L_{3j} \end{pmatrix} = 0 \text{ for every } i, j=2 \dots n \text{ with } i \neq j \quad (11)$$

This means that the 2x1 vectors, formed by the first and the third component of the \mathbf{L} columns, must all be parallel. Equation (11) may be simplified into:

$$\det \begin{pmatrix} L_{1j} & L_{1j+1} \\ L_{3j} & L_{3j+1} \end{pmatrix} = 0 \text{ for every } j=2 \dots n-1 \quad (12)$$

Considering that L_{1j+1} and L_{3j+1} depend on $q_1 \dots q_j$ and that L_{1j} and L_{3j} depend on $q_1 \dots q_{j-1}$, equation 12 gives the singular values of q_j as function of $q_1 \dots q_{j-1}$. Hence, in order to find the singular configurations, an iterative method can be performed:

- Solution of equation 12 for $j=2$. This involves only q_1 and q_2 . One or more curves formed by the couples (q_1, q_2) will be computed.
- For each of the previous couples (q_1, q_2) q_3 can be computed with equation 12 for $j=3$.
- Going on in this way for every previous $(q_1, q_2, \dots, q_{j-1})$ q_j can be computed with equation 12.

A joint limits control may also be added to avoid configurations leading to collision between the links that would never be possible to reach.

Equation 12 implies that, for the manipulator to be singular, all $q_1 \dots q_{n-1}$ must have an appropriate value. For e.g. it is not possible that, for a particular value of q_2 , the manipulator could be singular: for that value of q_2 all $q_1 \dots q_{n-1}$ must have an appropriate value according to equation 12. Hence, instead of what happens for the 6 DOF robot of section 4.1, it is not possible that every point in the Cartesian space might be singular, and therefore a graphic representation may be obtained. With the method exposed it is possible to compute all the $(q_1, q_2, \dots, q_{n-1})$ vectors for which the manipulator is singular. These values are enough to determinate the position of a point of the $n-1^{\text{th}}$ link, for e.g. for a point of the n^{th} joint axis, which belongs also to the n^{th} link. By finding these positions the Cartesian singular regions may be computed and then plotted.

Even if the Tecsas manipulator is not provided with reaction wheels, this method has been applied to it. The

Cartesian singular regions have been computed taking into account its corresponding joint limits. The results are reported in the following figure:

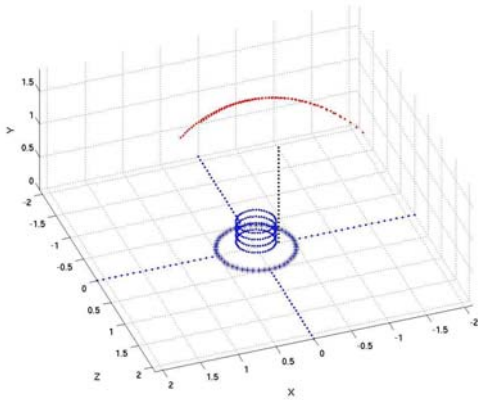


Figure 2 Cartesian singular regions

In the figure the chaser satellite and the first joint have been also sketched. The singular regions are only a small arc. This is the effect of the joint limits that strongly reduce the reachable singularity regions. It is easy to see that this arc lies in the vicinity of the workspace border. Therefore, in order to avoid them, it would be enough to keep the manipulator in the middle of the workspace. The figure also shows that no other singular curves appear within the workspace.

Although, as discussed in section 4.1, the possibility to provide such a graphical representation could greatly improve the effectiveness of the manipulator tele-operation control, it is worth noting that in a free-floating system, in which the joint rates are rarely higher than 5 deg./sec., such regions would never be reached. In fact, in the vicinity of a singularity, the joint rates rapidly increase if the end-effector desired velocity is not within the image of the Jacobian matrix computed in the singular configuration. Therefore the most important problem with a free-floating system is to find the configurations that, for a generic end-effector velocity, allow the joints rates not to exceed their limits. In order to handle this problem an algorithm optimizing, for a certain trajectory, the initial manipulator configuration and chaser state, and taking into account the joint rate limits, was developed.

5 Optimization algorithm

5.1 Introduction

If the target travels along a certain trajectory the ability to exactly track its Cartesian position and orientation with the manipulator end-effector by the human operator is essential to limit the forces developed during the impact at the grasp. This ability depends, in tele-operation, on the “feedback” between the operator and the system. Typically, the better the visualization system (a 3D screen would be the best choice) and the interface system, through which the operator can drive

the robotic system, the more precise the maneuver will result.

On the other hand, the possibility to keep the manipulator far from singular configurations may be improved by a good choice of the manipulator/chaser satellite initial state. For e.g., if the manipulator initial state is in the vicinity of a singularity the correct trajectory will probably only be kept for a short arc. On the contrary if at the beginning the system is far from a singularity it could be kept for a longer arc. It follows that the initial configuration of the manipulator/chaser satellite with respect to the target satellite can be optimized.

Hence an optimization algorithm has been developed in order to find the optimal initial system configuration. Since we must avoid the singularities rather than go through them, such an algorithm provides an initial configuration which allows the manipulator to avoid the singularities for the longest arc. The program has been developed in FORTRAN, resorting to Sequential Quadratic Program (SQP).

5.2 Program description

Since an optimization process must be performed, the optimization parameters, the cost function and the constraints must be defined.

The *optimization parameters* are the seven joint coordinates. The docking point initial position and the desired orientation of the end-effector with respect to the target satellite define the initial desired end-effector state. With the end-effector in the initial desired state, these parameters uniquely define the manipulator configuration and the chaser satellite position and orientation.

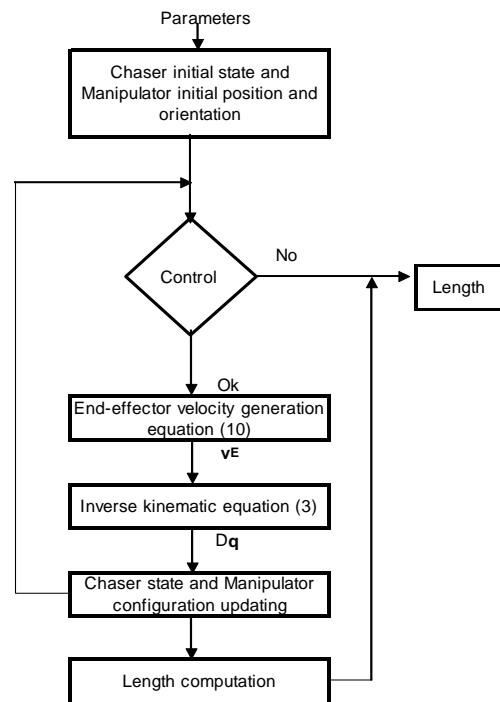


Figure 3. Cost function block scheme.

The *cost function* is the path length that the manipulator/chaser satellite can track, starting from the initial configuration, until one of the constraints is exceeded. Therefore the *constraints* are included in the cost function rather than being used in the optimization process. This choice is due to the simplicity of the resulting cost function definition. A block diagram of this function is given in figure 3.

The control is OK if the following constraints are satisfied: joint limits, joint maximum rate 5 deg./sec., minimum distance between the target and the chaser satellite 0.5 m, minimum value of the manipulability measure 10^{-3} . If it is not satisfied the path length is returned.

Since a path tracking operation must be simulated, a drift phenomenon occurs, as described in [6], while inverting the kinematics, because of numerical implementation errors. The linear and angular velocity of the end-effector \mathbf{v}_d , for the desired trajectory, and the error \mathbf{e} between the desired and actual end-effector position and orientation are used, as in [6], to generate the end-effector velocity \mathbf{v}_E , making the system asymptotically stable:

$$\mathbf{v}_E = \mathbf{v}_d + \mathbf{K} \mathbf{e} \quad (13)$$

where \mathbf{K} is a positive definite matrix. For the orientation error a quaternion based approach has been used to avoid mathematical singularities. The desired trajectory is a circumference, concentric with the target satellite, of radius 0.4 m, tracked with a angular velocity of 4 deg./sec.. The orientation of the end-effector relative to the target satellite must always remain the same.

The inverse kinematics is solved by equation (3), providing the joint coordinate increment $\Delta \mathbf{q}$. This is used to update the manipulator configuration and the chaser satellite position and orientation. As before the orientation is updated by resorting to a quaternion based approach.

Finally the loop is closed by controlling the updated state. In the mean time, the path length is computed.

5.3 Results

Because of the nonlinearity of the cost function, the optimal set of parameters strongly depends on the initial set used. In fact the algorithm is able to maximize the cost function only in the vicinity of the initial set of parameters. Hence several initial guesses of parameters must be tested in order to discriminate the absolute maximum of the function from the local ones.

rad	Set1	Set2	Set3	Set4	Set5
Joint 1	1.119	1.036	0.976	0.786	0.904
Joint 2	-1.421	-1.439	-1.479	-1.562	-1.543
Joint 3	-0.873	-0.751	-0.585	-1.032	-1.328
Joint 4	2.307	2.353	2.393	2.420	1.899
Joint 5	0.511	0.328	0.895	1.079	1.075
Joint 6	2.714	2.549	2.607	2.626	2.596
Joint 7	-0.466	-0.342	-0.169	-0.144	-0.1
Length (deg.)	246	233	90	138	104

Figure 4 Optimization results table

The results are reported in figure 4. As expected the initial set of parameters strongly influence the optimization process. The path tracking stops mostly because the joint velocity limits are reached. For the optimal solution, the spacecraft attitude is approximately constant. The overall computational time is about one minute.

6 Conclusions

In the present work the singularity problem for a free-floating system was analyzed and the results were applied to a realistic spatial system.

Firstly, the independence of the singularities of the end-effector Jacobian on the inertial parameters of the last link and on the last joint coordinate was demonstrated.

Secondly, the advantage of using reaction wheels was shown. For this case, the singularities were found analytically and their graphical representation in 3D space was described. With this configuration it was shown that the singularities are not so important, also with a mass ratio between the spacecraft and the manipulator of 1/7. On the other hand, the problem was raised with regard to the allowed joint rates, which can strongly limit the use of such a graphical representation.

Finally the possibility to avoid the singularities for a long path, also remaining within the joint rate limits, has been shown by use of optimization. Although no spacecraft attitude control is provided, the spacecraft attitude is in the optimal solutions only slightly affected.

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