Searching a valid hand configuration to perform a given grasp[★]

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Abstract: This paper presents a methodology to find a configuration of an anthropomorphic hand that satisfies some desire contact contact constraints on an object. The proposed approach has an on-line procedure, which iteratively looks for the final hand configuration starting from an initial one using the hand Jacobian, and an off-line procedure, which determines a set of initial configurations for the on-line procedure, using for this purpose heuristics obtained from the observation of the hand grasping an object and a statistical analysis of test trials. The off-line work is intended to simplify and speed up the on-line work that must deal with a thirty degrees of freedom system including the existence of close kinematics chains. The paper includes details of the approach implementation as well as some examples to illustrate the procedure performance.

1. INTRODUCTION AND MOTIVATION

Robotics has a very large field of applications and in different environments, like maintenance, rescue, assistance, among many other industrial and service applications, and applications can be either on Earth, underwater or in the space. There are applications like visual inspection in which the robot is used to carry a vision system and do not need to have physical contact with the environment, but most of the robotics applications need, at some point, to physically interact with the environment and, from these applications, a very significant percentage need to grasp and manipulate objects in the robot workspace. The advances in robot hands are significative (Bicchi, 2000), but the availability of these devices has associated some problems that still need better solutions than the existing ones. Among these problems there is the grasp planning. This usually involves a first decision (Cutkosky, 1989): using power grasps, which in general are obtained by closing the hand around the object without knowing the final contact points between both elements; or using a precision grasp, which in general requires the determination of specific contact points on the object that, of course, must be reached by a hand. A lot of work was focused on finding appropriate contact points on the object, e.g. for 2D objects Nguyen (1988), Park and Starr (1990), Liu (1998) and Cornellà and Suárez (2006, 2008), and for 3D objects Ponce et al. (1997), Borst, Fischer and Hirzinger (1999), Li, Hsu and Sastry (1989), Pollard (2004) and Roa and Suárez (2007). This problem frequently appears also in object fixturing in industrial applications, but there are not general formulations that can solve precision grasp including the kinematics constraints of a given hand (Morales et al., 2006; Rosell et al., 2005; Rosales et al. 2008). Therefore, using the inverse kinematics of a particular hand to check whether or not it can reach some given grasping points on the object is a problem of practical interest, and, if the hand can reach those grasping points, returning the hand configuration to do it is the next useful result. In this context, this paper proposes an approach to find the configuration of an anthropomorphic hand that satisfies some desire contact constraints. The main difficult of this problem when traditional inverse kinematics approaches are considered is the large number of involved degrees of freedom and the existence of close kinematics chains. In the proposed approach some heuristics obtained from the observation of the hand when an objects is grasped are used to simplify the search of a solution, which is performed using a particular iterative implementation based on the hand Jacobian.

2. PARTICULAR PROBLEM CONDITIONS

This section introduces some particular conditions related with the mechanical hand MA-I used in the experiments (Figure 1) as well as with the contact points specification.

From the hand side it is considered that:

- The hand is anthropomorphic, with four fingers (the thumb, the index, the medium and the ring fingers). Each finger has four independent degrees of freedom (DoF). This means the existence of 16 DoF from the four finger joints plus 6 DoF from the hand wrist movements.
- The contact points must be on the proper region of each fingertip. The fingertips are considered spherical, and the contact region is given by approximately a quarter of the sphere surface (see figure 2). Since two parameters are needed to identify a point on each fingertips, this means the existence of 8 additional DoF (2 per fingertip).
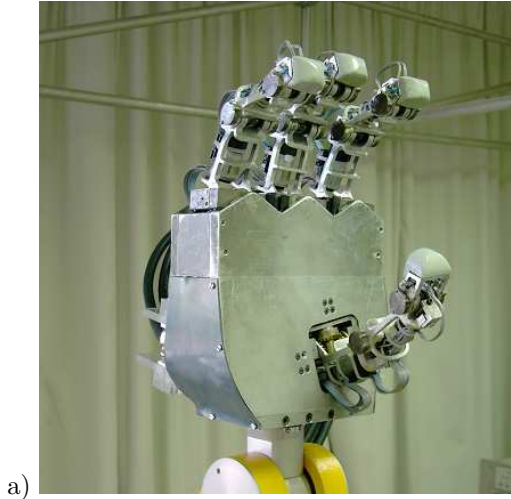
Then, the problem involves a total of 30 DoF.
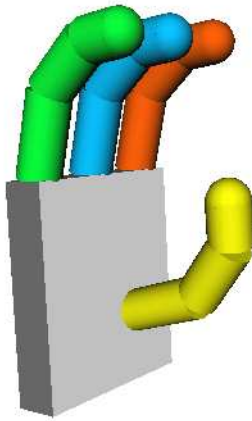
From the contact points side it is considered that:

- Each contact point is defined by five parameters, three of them being the three coordinates of the point

a)

b)

Fig. 1. a) Mechanical hand MA-I with four fingers with four DoF each one; b) simplified model used for the collision checking.

in the physical space, and the other two describing the direction normal to the object boundary at that point. Note that a grasping contact point does not impose an orientation constraint around the direction normal to the object boundary. Basically, the contact point information says where the finger must touch the object and in which direction there must be a non-null force component.

- The assignment of the fingers to the contact points is known. In real problems this may not be always true, and in such a case the proposed procedure should have to be applied to all the possible combinations of four assignments while a solution is not found (in practice some heuristics may easily prune some non-valid cases).

The final hand configuration has to be an actual reachable one, this means that hand configurations that imply intersections or collisions among the fingers or the palm are not acceptable (even when they are theoretically possible due to the movement ranges of the joints). But on the other hand, since the work is done for a set of contact points in the space, potential collisions between the hand and the environment are not considered (this is considered as future work to be done in parallel with the planning of the
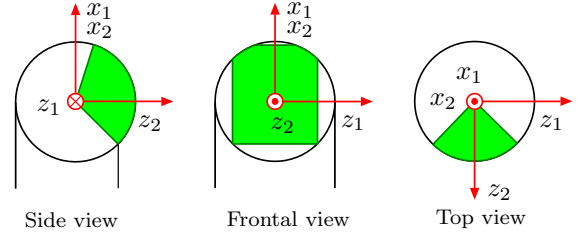

Fig. 2. Fingertip area considered for the contact between the finger and the object.

hand movements toward the grasping configuration in the real workspace).

3. OVERVIEW OF THE PROPOSED APPROACH

The proposed approach is based on the combination of the classical use of the Jacobian with some particular heuristics developed from the analysis of hand movement capabilities. The main steps of the general procedure are:

(1) Based on the four given contact points in the space, determine an initial hand configuration that satisfies the constraints for the thumb and provides a particular orientation of the wrist. This is done using the results of an off-line original statistical analysis of initial hand configurations that increases the performance of the approach.
(2) Determine the Jacobian of the hand using as reference the position and orientation of the thumb fingertip. The Jacobian is computed in a classic way, but as a difference with previous approaches it is referred to the thumb fingertip.
(3) Starting from the initial hand configuration, use the Jacobian of the hand to iteratively find a new hand configuration that decreases the distance from the current positions of the fingers to the desired ones. The distance is evaluated in the 5-dimensional space of the constraints imposed to each finger.
(4) If a given ending condition is not satisfied, modify the initial position and go to Step 3, else return the hand configuration.

These steps and the related concepts are detailed in the following subsections.

3.1 General nomenclature

The following general nomenclature will be used along the paper:

ϕ_{ij}: value of a finger joint, with (see Fig 3):
- $i = 1, ..., 4$ identifying the finger (1=index; 2=medium; 3=ring; 4=thumb).
- $j = 1, ..., 6$ identifying the joint (1=adduction-abduction; 2,3,4= flexion-extension; 5,6= virtual joints defining the contact point at the fingertip).

$C = (W, \phi_{11}, ..., \phi_{16}, ..., \phi_{41}, ..., \phi_{46})$: hand configuration, with W being a 6-dimensional vector fixing the wrist position and orientation. Note that C is a 30-dimensional vector. The subindices f, o and k will be used to indicate the final, the initial and a generic configuration in the iteration k of the algorithm, respectively.
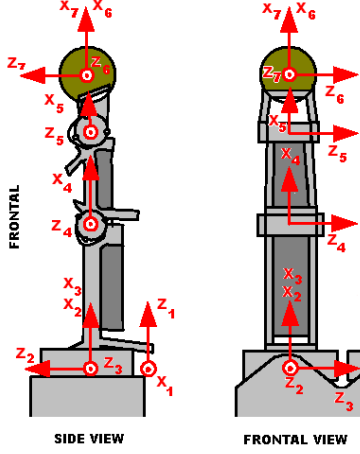
Fig. 3. Kinematic model of a finger.

$\boldsymbol{p}_i = (p_{x_i}, p_{y_i}, p_{z_i})$: vector describing the position of the contact point of finger i in the physical space. The supraindices $*$ and k will represent, respectively, the desired value and the actual value on the fingertip at the iteration k.

$\boldsymbol{r}_i = (r_{x_i}, r_{x_i}, r_{z_i})$: vector describing the position of the center of the fingertip i in the physical space. The supraindices $*$ and k will represent, respectively, the desired value and the actual value at the iteration k. Note that if $\boldsymbol{p}_i$ is given then $\boldsymbol{r}_i$ can be defined with only two parameters because $\|\boldsymbol{p}_i - \boldsymbol{r}_i\|$ is a constant distance (the radious of the spherical fingertip).

$P = (\boldsymbol{p}_1, \boldsymbol{r}_1, \boldsymbol{p}_2, \boldsymbol{r}_2, \boldsymbol{p}_3, \boldsymbol{r}_3)$: auxiliar vector. The supraindices $*$ and k will represent, respectively, the desired value and the actual value at the iteration k.

3.2 Computation of the initial hand configurations

Computation of a initial configuration. Looking for the final hand configuration C_f using the Jacobian requieres the use of an initial hand configuration C_o. The computation of a configuration to be used as C_o in the search algorithm is as follows:

(1) The hand is initially positioned such that the constraints imposed to the contact of the thumb are satisfied. This is done by imposing the conditions:

$$\boldsymbol{p}_4 = \boldsymbol{p}_4^* \qquad (1)$$

$$\boldsymbol{r}_4 = \boldsymbol{r}_4^* \qquad (2)$$

This is equivalent to five independent constraints, so there are still $30 - 5 = 25$ variables to be defined.

(2) The adduction-abduction joints are fixed in the middle of their ranges, and the contact points are located in the middle of the fingertips. This is done by imposing the variables ϕ_{i1} and ϕ_{i6}, $i = 1, ..., 4$ to be in middle of their ranges. This is equivalent to eight independent constraints, so there are still $25 - 8 = 17$ variables to be defined.

(3) The remaining sixteen finger joints are expressed as a function of one parameter $\lambda \in [0, 1]$ that indicates how open or close is the hand (a proper selection of a sequence of λ values, described below, produces

different useful initial hand configurations). This is done as:

$$\phi_{ij} = \lambda \, \phi_{ij_{min}} + (1 - \lambda) \, \phi_{ij_{max}} \qquad (3)$$

with $i = 1, ..., 4$ and $j \neq 1 \neq 6$. For $\lambda = 0$ the fingers are fully flexed and for $\lambda = 1$ the fingers are fully extended. It must be remarked that $\lambda = 0$ produces a "virtual" collision between the fingers and the palm, but it is just a theoretical configuration for the initialization of the algorithm that is not really produced in practice, therefore this virtual collision is not a problem. Equation (3) is equivalent to 16 independent constraints, so there is still $17 - 16 = 1$ variable to be defined.

(4) The remaining degree of freedom corresponds to the rotation ϕ_T of the hand around the direction normal to thumb contact point (i.e. normal to $\boldsymbol{p}_4 - \boldsymbol{r}_4$), and it is fixed trying to locate the hand such that the index and ring fingers are well oriented with respect to their final positions. This is done by minimizing the angle between two vectors $\boldsymbol{v}_1$ and $\boldsymbol{v}_2$ defined as follows. Let Π_T be the plane orthogonal to $\boldsymbol{p}_4 - \boldsymbol{r}_4$ and containing the thumb contact point $\boldsymbol{p}_4$, then:

$$\boldsymbol{v}_1 \text{ is the projection of } \boldsymbol{p}_3^* - \boldsymbol{p}_1^* \text{ on } \Pi_T \qquad (4)$$

$$\boldsymbol{v}_2 \text{ is the projection of } \boldsymbol{p}_3 - \boldsymbol{p}_1 \text{ on } \Pi_T \qquad (5)$$

After this step, the 30 variables that fix C_o are completely defined.

Selection of a sequence of λ for the computation of the initial configurations. The determination of a sequence of values of λ that fix the successive initial configurations of the hand used in the main algorithm (until a solution is found or until a given number of initial configurations was reached) are obtained off-line, thus it is not a time consuming operation during the on-line determination of a grasping hand configuration when a desired real constraint P^* is given. The sequence S of values of λ is obtained as follows:

(1) Generate a large enough set $\mathcal{P}$ of random constraints P^*.

(2) Generate a uniformly distributed set of N_λ values of $\lambda_l \in [0, 1]$.

(3) For each λ_l, $l = 1, ..., N_\lambda$ obtain an initial hand configuration C_{o_l} as it was described in the previous procedure.

(4) For each constraints $P^* \in \mathcal{P}$, use C_{o_l}, $l = 1, ..., N_\lambda$ (one at a time), to look for a final hand configuration using the main iterative search algorithm (described below in Section 3.5). For each λ_l a given percentage of success is obtained.

(5) Select the value of λ_l with higher percentage as the first element $S[1]$ in the sequence.

(6) Remove from $\mathcal{P}$ the constraints P^* for which a solution was obtained using the values of λ already included in S. For each λ_l not included in S a given percentage of success is obtained considering the remaining constraints P^*.

(7) Select the value of λ_l with higher percentage as the next element $S[k_\lambda]$ in the sequence.

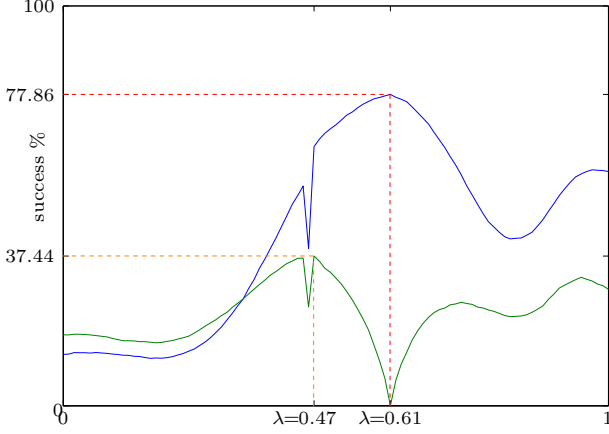(8) Iteratively applied steps 6 and 7 to obtain a desired number of elements $k_{\lambda_{max}}$ in the sequence S.

Fig. 4. Selection of the first two values of λ in the sequence S.

k_λ	1	2	3	4	5
$S[k_\lambda]$	0.61	0.47	0.95	0.46	0.73

6	7	8	9	10
0.00	0.45	0.89	1.00	0.37

Table 1. Sequence $S[k_\lambda]$, $k_\lambda = 1, ..., 10$.

As an example, the search of the first two elements of the sequence S for the hand MA-I is illustrated in Fig 4. A training set $\mathcal{P}$ with $10,000$ constraints P^* was generated (step 1) and a set of $N_\lambda = 100$ values of λ_l were uniformly selected in the range $[0,1]$ (step 2). For each value of λ_l an initial hand configuration C_{o_l} was computed, and then used to search a solution for each constraint P^* (steps 3 and 4); the obtained percentages of success are shown by the line in Fig 4 with a maximum of $77,86\%$ for $\lambda_l = 0.61$, which becomes the first value of λ in the sequence S (step 5). Removing the already solved constraints P^* and solving the remaining ones for values of $\lambda_l \neq 0.61$, the obtained percentages of success are shown by the line in Fig 4 with a maximum of 37.44% for $\lambda_l = 0.47$ (step 6), which is selected as the second value of λ in the sequence S (step 7).

This procedure was used to compute a sequence of 10 values of λ (i.e $k_{\lambda_{max}} = 10$) for the hand MA-I, the obtained results are shown in Table 1. Fig 5 shows the accumulated percentages of success (for $k_\lambda = 1, ..., 10$) on the training set $\mathcal{P}$ for each λ_l.

3.3 Hand Jacobian and computation of the increments of the hand joints

The Jacobian relates the velocities at the hand joints with the velocities (linear and rotational) at the fingertips. The orientations of the fingertip around the contact point is implicitly treated by considering the position of the contact point itself, $\boldsymbol{p}_i$, and the position of the center of the fingertip $\boldsymbol{r}_i$; this simplifies the representation of the Jacobian. Then, the relation used in this work is the well known
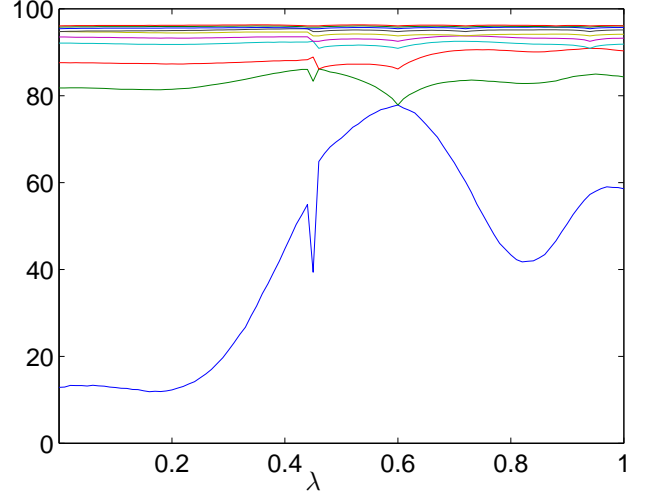
$$\Delta P = J \Delta Q \qquad (6)$$

where

Fig. 5. Accumulated percentages of success for $k_\lambda = 1, ..., 10$.

$\Delta P = \alpha(P^* - P_k)$, being α a constant gain value (empirically determined) to obtain a good convergence of the algorithm.

$\Delta Q = Q_k - Q_{k-1}$, being $Q = (\phi_T, \phi_{11}, ..., \phi_{46})$.

Note that ΔP has dimension 18×1, ΔQ has dimension 25×1, and therefore J is a 18×25 matrix.

Then, ΔQ is computed by solving eq. (6) as

$$\Delta Q = J^+ \Delta P \qquad (7)$$

where J^+ is the pseudoinverse of J.

3.4 Ending conditions

The iterative search algorithm finishes when one of the following ending conditions is satisfied.

(1) The hand configuration satisfies the desired contact point constraints, i.e. $P_k \simeq P^*$. The ending condition is, $\forall i$,

$$\|\boldsymbol{p}_{i_k}^* - \boldsymbol{p}_{i_k}\| < d_{min} \text{ and } \|\boldsymbol{r}_{i_k}^* - \boldsymbol{r}_{i_k}\| < d_{min} \qquad (8)$$

where d_{min} is a fixed threshold value.

(2) A maximum number $k_{\lambda_{max}}$ of initial configurations C_o has been tested. The ending condition is:

$$k_\lambda = k_{\lambda_{max}} \qquad (9)$$

For each of these initial configurations C_o the number of iterations is limited such that:

- A maximum number k_{max} of iterations has been done, i.e.

$$k = k_{max} \qquad (10)$$

- The progress of the current hand configuration C_k towards the desired one C_f is not significant, which means that for n consecutive iterations $P_k \simeq P_{k-1}$, which is verified as

$$\sum_1^4 (\|\boldsymbol{p}_{i_k} - \boldsymbol{p}_{i_{k-1}}\| + \|\boldsymbol{r}_{i_k} - \boldsymbol{r}_{i_{k-1}}\|) < s_{min} \qquad (11)$$

where s_{min} is a fixed threshold value.

3.5 Main iterative search procedure

The following functions, combined with the ending conditions described in the previous subsection, are used to search the hand configuration that satisfies the desired constraints:

- Obtain_Initial_Config(λ, P^*): computes the initial hand configuration C_o given λ and the initial constraints of the problem P^* (see Subsection 3.2).
- Compute_Jacobian(C_k): computes the pseudo-inverse J_k^+ of the hand Jacobian for a given hand configuration C_k.
- Compute_Hand_Config(C_k, J_k^+, P^*): computes the hand configuration C_{k+1} using the current hand configuration C_k, J_k^+, and P^* (see Subsection 3.3). This function takes into account the range of each joint value; if a joint tends to be out of range it is forced to remain in its closest range limit.
- Obtain_P(C_k): computes the center of the fingertips and the expected contact points on them from the hand configuration C_k using the direct kinematics (note that C_k includes the position of the two virtual joints at the fingertips).
- Check_Collisions(C_k): checks the existence of collisions between the elements of the hand for the configuration C_k, returning TRUE or FALSE according to whether there are collisions or not.

The algorithm is:

$k_\lambda = 1$
WHILE $k_\lambda \le k_{\lambda_{max}}$ DO
    $\lambda = S[k_\lambda]$
    $C_o = $ Obtain_Initial_Config(λ, P^*)
    $k = 1$
    $h = 0$
    $C_k = C_o$
    $P_k = $ Obtain_P(C_k)
    WHILE $k \le k_{max}$ AND $h < n$ DO
        IF $P_k \simeq P^*$ THEN
            IF Check_Collisions(C_k) = FALSE THEN
                RETURN(C_k)
        $J_k^+ = $ Compute_Jacobian(C_k)
        $C_{k+1} = $ Compute_Hand_Config(C_k, J_k^+, P^*)
        $k = k + 1$
        $P_k = $ Obtain_P(C_k)
        IF $P_k \simeq P_{k-1}$ THEN $h = h + 1$
        ELSE $h = 0$
    $k_\lambda = k_\lambda + 1$
RETURN('Fail')

4. IMPLEMENTATION AND EXAMPLES

The proposed approach was implemented using C++ language. The following libraries have been used:

- Qt: Library to set a graphic environment (QT, 2008).
- Coin3D: Library to visualize the 3D virtual model of the hand (COIN3D, 2008).
- PQP: Library to check collisions (PQP, 2008).

As an application example, it is desired to locate the hand satisfying the constraints P^* shown in Fig 6a, which were obtained by generating a random hand configuration, and randomly choosing the contact directions by
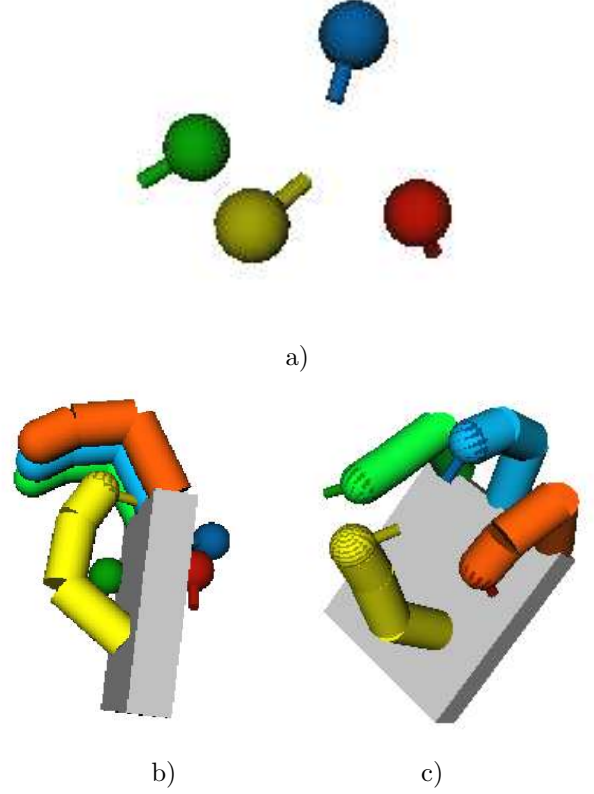

Fig. 6. a) Desired final positions and orientations for the fingertip contacts P^*; b) initial hand configuration C_o; c) final hand configuration C satisfying the constraints.

choosing a contact point on the each fingertip; the figure illustrates the desired final positions of the fingertips and the directions in which the contacts take place. Using the methodology described in Section 3.2 the initial hand configuration C_o shown in Fig 6b is obtained for the first λ in the sequence S (i.e. $\lambda = S[1] = 0.61$), and from it the final solution shown in Fig 6c was generated in fifteen jacobian iterations ($k = 15$) in 24 ms. The constraints P^* are also represented in Fig 6b and c in order to allow the visualization of their relative positions with respect to the initial and final hand configurations. The parameters used in the algorithm were: $k_{\lambda_{max}} = 10$, $k_{max} = 1000$, $\alpha = 1$, $d_{min} = 1$ mm, $s_{min} = 0.05$ mm and $n = 20$.

Using the same parameters, a second example requiring the use of two initial configurations to find the solution is illustrated in Fig 7 and Fig 8. Fig 7 shows the results for the iteration with the first value of λ in the sequence (i.e. $\lambda = S[1] = 0.61$): Fig 7a shows the initial hand configuration C_o obtained for $\lambda = 0.61$, Fig 7b and c show two intermediate iterations, and Fig 7d shows the final result (after 10 iterations in 16 ms), which satisfies the contact constraints but is not valid since it is not actually reachable due to a collision between two fingers. Fig 8 shows the results for the iteration with the second value of λ in the sequence (i.e. $\lambda = S[2] = 0.47$): Fig 7a shows the initial hand configuration C_o obtained for $\lambda = 0.47$, Fig 7b and c show two intermediate iterations, and Fig 7d shows the final result (after 4 iterations in 6 ms), which is

Fig. 7. a) $k = 1$; b) $k = 2$; c) $k = 3$; d) $k = 10$.

Fig. 8. a) $k = 1$; b) $k = 2$; c) $k = 3$; d) $k = 4$.

valid since it satisfies the contact constraints and does not produce any collision between the hand parts.

5. CONCLUSIONS

The papers presents a procedure to obtain the grasp configuration of an anthropomorphic hand when the contact constraints are given, for instance generated by a grasp planner. The approach combines the classical use of the Jacobian with some particular heuristics developed from the analysis of hand movement capabilities; it was implemented and the results are satisfactory. A particular example is shown in the paper to illustrate the approach.

Future work is oriented to consider the potential collisions of the hand with the objects in the work environment and the inclusion of the procedures in a general hand motion planner.

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Rosell, J., X. Sierra, L. Palomo, and R. Suarez (2005). Finding grasping configurations of a dexterous hand and an industrial robot. IEEE Int. Confer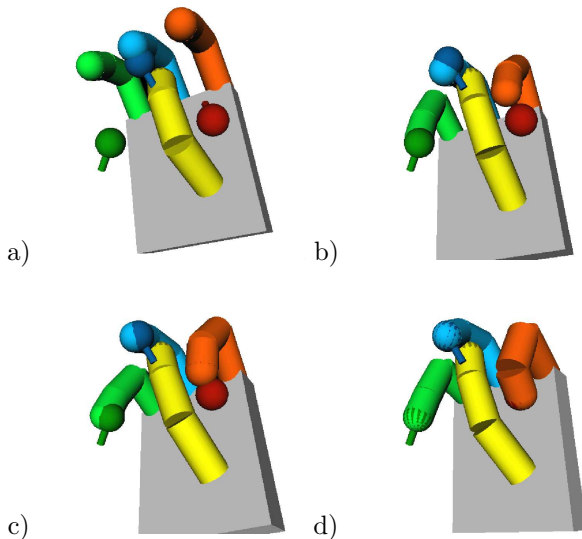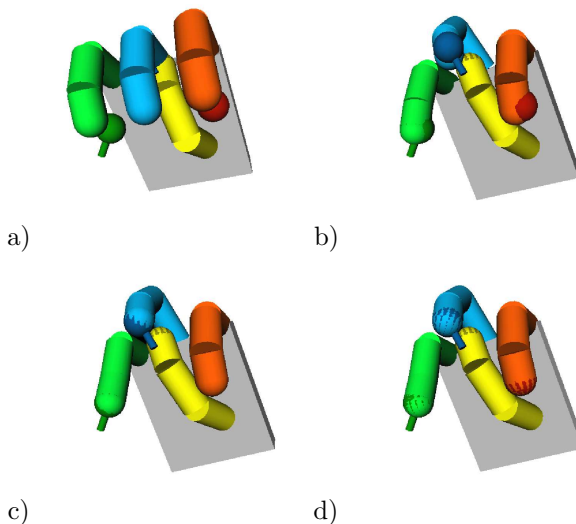ence on Robotics and Automation, ICRA 2005, pp. 1178-1183.