# Grasp Quality Improvement with Particle Swarm Optimization (PSO) for a Robotic Hand Holding 3D Objects

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Abstract: Automated grasp planning for robotic hands is a complex problem when compared with the ease with which human hands grasp objects. Research in robotic grasp synthesis attempts to find novel ways in which a stable grasp can be achieved reliably. In this work, we present a grasping methodology that achieves optimized force closure grasps on 3D irregular objects. 3D objects in the form of polygonal meshes are parameterized to 2D shapes in order to reduce the search space by constraining robotic hands finger tips to be in contact with the objects surface. We use a Particle Swarm Optimization (PSO) based framework to optimize an initial grasp. The scheme has been validated on test-case 3D objects represented with surface tessellation for a 5-fingered DLR robotic hand.

## 1 INTRODUCTION

Robotic arms are one of the most common applications in automation and intelligence based systems. The robot arm is usually a serial link manipulator, and is provided with a parallel jaw gripper fitted as the end effector. Parallel jaw grippers suffer major disadvantages, while handling objects to be handled with arbitrary shapes and uneven surfaces (Shimoga, 1996). Better robot grasping abilities are assured by fitting robotic arms with end effectors, which are adept at matching human hand-like motions. The research in the field of robot grasping tries to address three different issues viz. existence, analysis and synthesis of grasps. The study of robot hands and grasping are sharply differentiated from the design of fixtures and industrial grippers, which have extensive usage currently. Moreover, grasping research (especially synthesis) is devoted to generating schemes to find the best possible location to hold the object.

The design of the 3-fingered robot hand (Mason and Salisbury, 1985) largely initiated the tone for research in the field along with studies on prehension (Asada, 1979). The notion of grasp quality was introduced in order to provide a metric for successful grasps, (Ferrari and Canny, 1992). This was defined as the radius of the largest wrench space ball, centered at the origin, which can just fit within the unit grasp wrench space. Mathematical analyses were also presented by comparing various metrics (Mishra, 1995).

Grasp synthesis problems are tackled using analytical and empirical methods in literature and using a few other different grasp quality measures were also reviewed (Suárez et al., 2006).

Analytical grasp synthesis studies are based on a combination of geometric, kinematic and dynamic formulations. Modeling and solving problems by this approach is computationally intensive. The earliest works (Lakshminarayana, 1978) specify sufficient conditions of form closure of 2-D and 3-D objects. Thereafter, necessary conditions for 4-finger force closure grasps were published (Ponce et al., 1997).

Empirical methods give emphasis to techniques co-relating object features with robot hand. A case in example (Li et al., 2007) uses 3-D models of the object for shape matching with samples from a database of grasps. Another offshoot of this thread uses learning algorithms (Romero et al., 2008) where grasp images are searched for fundamental matching with the one demonstrated.

It is interesting to note that robotics research in grasping also leans on the study of an elaborate taxonomy of human grasps (Cutkosky, 1989). As



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mentioned, in the introduction, the pinnacle of grasp perfection would need to exploit designs based on anthropomorphism (even partially) in order to mimic the human hand (Biagiotti et al., 2004).

As a natural consequence, due to the complexity of such hands, attempts are made to reduce the search spaces (Li et al., 2003). In analytical methods, the complexity is reduced by accounting for the constraints formed by the coupling of various finger joints. The Barrett Hand Grasper uses such interlink transmissions reducing the total number of actuators (Townsend, 2000). Grasp synthesis algorithms are often handicapped by the limitation of the input representation of the objects and/or the semantics of the required tasks. This naturally introduces errors in the object registration/approximation by the grasp planner. Hence the synthesis strategy should fortify itself by generating a broad set of contact locations which in essence would lead for a robust grasp. Independent Contact Regions (ICR) provided leeway in the finger positioning (Nguyen, 1988).

Efforts are also directed in empirical methods towards the simplification of 3-D shapes by planar representation (Morales et al., 2006). A similar work (Aarno et al., 2007) utilizes representations based on 3-D contours.

The problem of grasp scheme generation is exacerbated by the infinite types of objects to be handled by numerous hand shapes/designs. Hence, there is an ever-present incentive to devise novel schemes for grasp synthesis which provide quality grasps elegantly.

## 2 PROBLEM OUTLINE

The objective of the present work is to find quality grasps on 3D objects. The grasps are synthesized for the robotic DLR/HIT Hand II model. The DLR/HIT Hand II has been jointly developed by DLR (German Aerospace Center) and HIT (Harbin Institute of Technology). The objects, for which the grasps are evolved, are represented with surface tessellation.

### 2.1 Grasp Planner Inputs

A triangular tessellation mesh has been used for the objects used for the trial experiments to generate grasp and validate the scheme. The density of the tessellation set, Ω, determines the detail with which the object features are represented. The points on the object surface are provided with position vectors, $\boldsymbol{p_i}$ with respect to the centre of mass (C.M) of the object and the unit normal vector, $\boldsymbol{n_i}$ of the corresponding triangle.

### 2.2 Wrenches and Contact

The robot hand finger-tip on the object surface generates a force on the object at the surface point. A corresponding torque with respect to the C.M. is also created. The concatenation of this force-torque vector represents the associated wrench, $\boldsymbol{\omega_r}$ applied by the finger-tip on the object surface at a location denoted by $\boldsymbol{i}$. A Coulomb friction model has been assumed, in the present work, for point contact between the finger-tip and the object. In order to assure that there is no slippage between the object and the robot hand at the finger-tips, it is necessary that the applied contact force vector should lie within the friction cone. The friction cone is linearized with an 8-sided pyramid. The coefficient of friction used is taken as 0.4

### 2.3 Grasp Quality Optimization

In the current work, the quality of the grasp is improved by particle swarm optimization (PSO), a heuristic method, which performs a global search. The global search is performed over the object surface points with a view to increase the grasp quality. Hence, the objective function, for the current work, is the grasp quality.

The grasp quality objective function, for optimization, is formed with a component which uses the condition number of the hand Jacobian, $\boldsymbol{H}$. A better quality (of this component) for the grasp indicates a better manipulability of the grasped object by the hand. This is expressed as the ratio of the maximum and minimum singular values of $\boldsymbol{H}$ i.e. $\boldsymbol{n_c(H)}$ (Shimoga, 1996). The best quality for this component i.e the best value possible is 1. In addition to this factor, a variation of the criterion of largest ball (Ferrari and Canny, 1992) grasp quality is used here, which is the radius of the largest ball, $\boldsymbol{\rho}$, within the convex hull formed by the wrenches, irrespective of the reference (Teichmann, 1996). The expression for the grasp quality, $\boldsymbol{Q}$, as a combination with these two components, with normalization, is expressed as,

$$\mathrm{Q} = \rho - 1000[1/\mathrm{n_c(H)}]) \quad (1)$$

### 2.4 Particle Swarm Optimization

The implementation of the PSO, in the current work, utilizes combination of the pattern-search method with the traditional PSO global search algorithm (Vaz et al., 2007).

The individual finger-tips of the five-fingered robot hand touch the object on the surface points. An initial FC grasp is generated using trial and error. The finger-tip contact points on the object's surface are then mapped to the 2d parameterized surface as discussed in the section 3. These set of five points along with hands position and orientation, formed as a vector are taken as one of the initial population member where others are chosen randomly. The parameterized surface is chosen as the solution space over which the PSO searches for the solution. The linear equations of the boundaries of the 2d parameterized surface are taken as the lower and upper bounds for the solution space.

The swarm size for the PSO is taken as 42. The social and cognition parameter values are both 0.5. The initial and final inertia weights are 0.9 and 0.4 respectively. A maximum function evaluation of 10,000 is provided as the stopping criterion for the optimization method.

## 3 MESH MAPPING

The object surface has a specific discrete set of points, available to the planner, on which the grasp search can be conducted. This simple and efficient procedure, though adequate can be further mapped to a modified surface which allows a thorough and continuous search by the use of mesh parameterization (Floater et al., 2005, and Hormann et al., 2007).

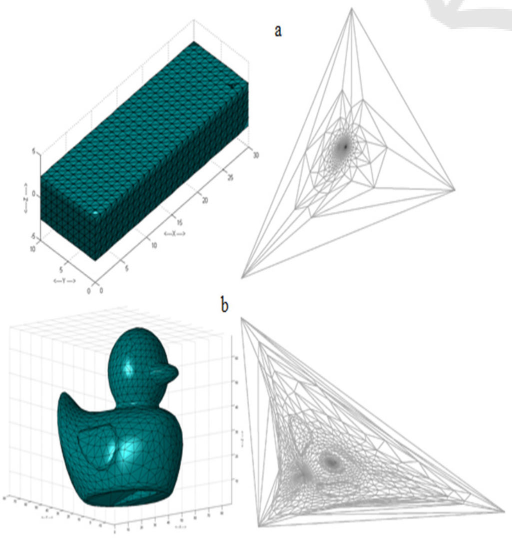


Figure 1: The 2D parameterizations of the surface tessellations for the 3D Objects used for validating the grasp synthesis schema (a) Rectangular parallelepiped. (b) Duck.

The 3D object surface mesh is parameterized to an equivalent 2D surface. A triangle constituting a unit of initial tessellation set, Ω, is removed. This creates an equivalent homeomorphic disc from the remaining surface of the 3D object.

In order to ensure and enable a continuous search region on the object surface, Barycentric co-ordinates are used. The 3D objects for the experimental trials, in this work, are shown in Figure 1 (Rakesh et al., 2015) along with the corresponding 2D mesh parameterizations. The search for quality grasps are carried out on a rectangular parallelepiped and a duck as the 3D objects as shown and is described in the subsequent sections.

## 4 EXAMPLE CASE-STUDIES

A DLR robot hand with five fingers has been used on two objects within the MATLAB frame-work for testing the synthesis of the quality grasps as discussed hitherto. The objects consist of 3D models of a rectangular parallelepiped and a duck as shown in Figure 1. The parallelepiped surface consists of 1879 tessellation triangles. On the other hand, the duck is represented with moderate surface tessellation of 2055 triangles.

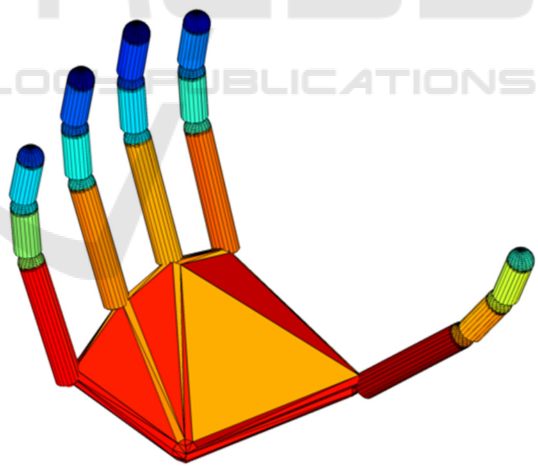

Figure 2: The DLR hand used for the case-studies.

The DLR robot hand, shown in Figure 2, consists of five fingers. For each fingers, the segments $l_1$ is 55 mm. The segments $l_2$ and $l_3$ are equal and represent a length of 25 mm each. The abduction/adduction movement is represented by $\theta_0$ at the base of each finger and the in-plane degree-of-freedom (DOF) for the joint at the same location is denoted by $\theta_1$. Hence, the base of each finger consists of 2-DOF joint. The subsequent in-plane finger joint rotations are denoted by $\theta_2$ and $\theta_3$ which are equal to each other, in the present case.

The skeletal connectivity diagram of the DLR hand is shown in Figure 3. The inverse kinematics relations for the fingers are detailed in the Appendix.

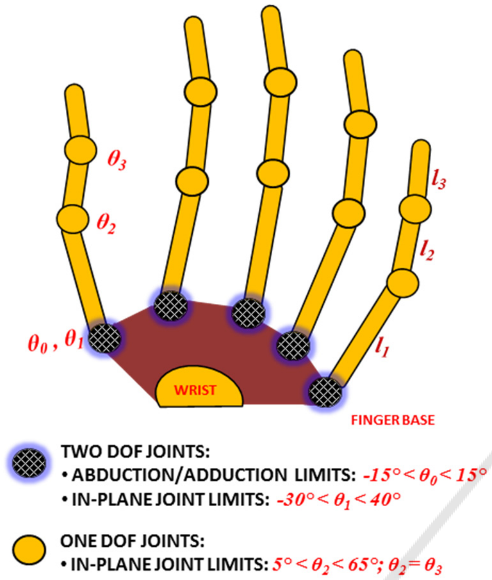


Figure 3: The skeletal connectivity diagram for the DLR hand used for the case-studies.

The Syngrasp frame-work (Malvezzi et al., 2013) within the MATLAB programming environment has been used to implement the scheme, on a personal computer with Intel i3, 2.2GHz processor.

### 4.1 Case-study: Rectangular Parallelepiped

The DLR robot hand is initialized with a grasp as shown in Figure 4 for the rectangular parallelepiped. The initial grasp quality is 11.08.

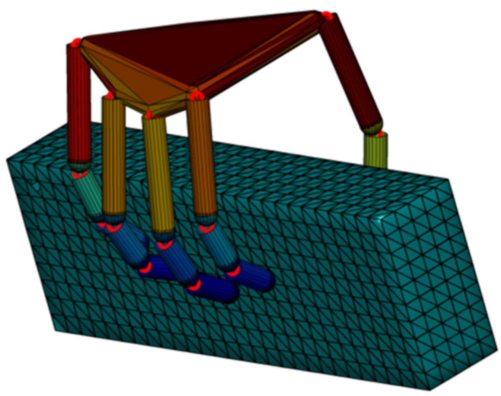

Figure 4: The initial grasp of the DLR hand on the rectangular parallelepiped.

The optimized grasp with a final grasp quality of 26.38 is generated as shown in Figure 5.

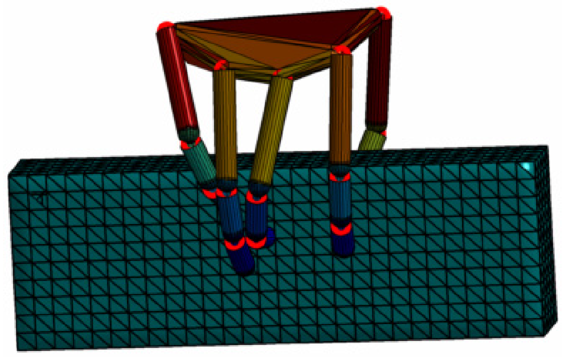

Figure 5: The final grasp of the DLR hand on the rectangular parallelepiped.

The iteration progress during the optimization for increasing the grasp quality is given in Figure 6.

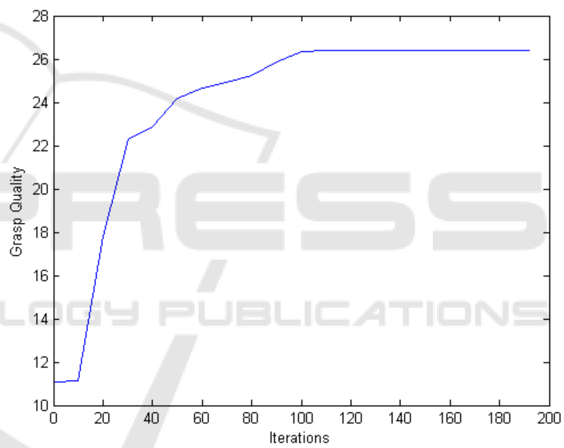


Figure 6: The increase in the grasp quality for the DLR hand and the rectangular parallelepiped.

The total time take for the optimization run is 47.6 s.

### 4.2 Case-study: Duck

The duck model with a moderate tessellation value of 2055 triangles forms the second sub-case for the test studies in this work.

The initial grasp with a quality of 13.036 is shown in Figure 7.

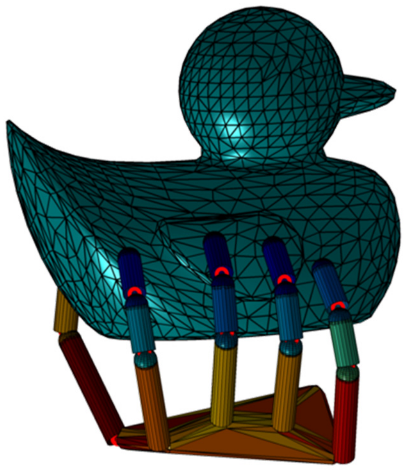

Figure 7: The initial grasp of the DLR hand on the duck.

On implementing the PSO for increasing the grasp quality the final grasp generated is shown in Figure 8.

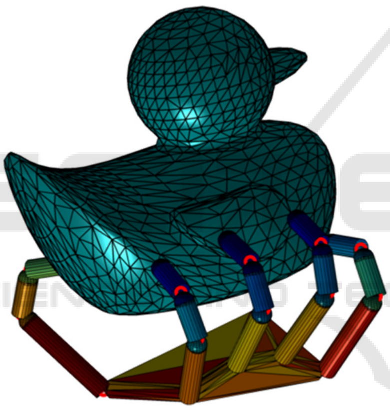

Figure 8: The final grasp of the DLR hand on the duck.

The total time taken for improving the grasp quality to 21.85 for the duck is 90 s.

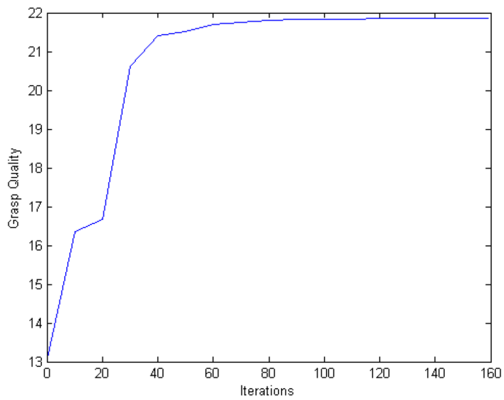


Figure 9: The increase in the grasp quality for the DLR hand and the duck model.

The progress of the iterations is shown in Figure 9.

## 5 CONCLUSIONS

The current work has formulated a scheme for grasp quality optimization with a robot hand for test case objects, based on PSO. The routine performs fairly well over a simple model like parallelepiped and also a comparatively complex geometrical model of duck. The reasonably fast run-times show the efficacy of the formulation for generating quality grasps quickly. Using an analytical method for computing inverse kinematics of the hand contributes to the lower times in grasp computation.

It is difficult to process complex objects analytically with the objective of automation in grasp synthesis. Moreover, in most of the applicable cases the computational times are disparagingly high. In this context, the current work has suitably validated the synthesis of quality grasps in a virtual environment. The applicability of the method on a simulated test bench helps to eliminate expensive hardware trials and manufacturing cycles, while reducing the implementation costs. Hence, the current work has been a successful endeavour for quality grasp synthesis and optimization, as a generalized planner for a different of objects, using PSO.

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## APPENDIX

The inverse kinematics for a particular finger can be derived geometrically. Analogous relations are valid for each of the fingers. It may be noted that adduction/abduction movement (***θ₀***) about the finger base gives rotation about the Y-axis. At a specific abduction/adduction angle (***θ₀***) the in-plane configuration of the finger is shown in Figure 10 along with the corresponding relevant nomenclature.

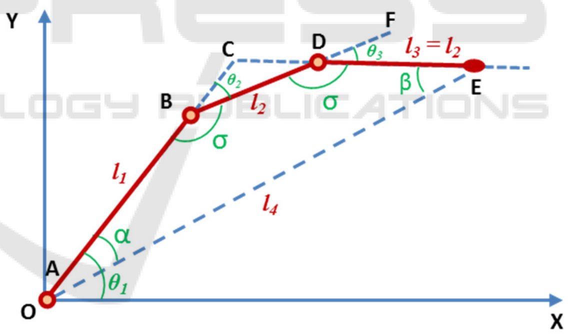


Figure 10: Geometrical method to for the inverse kinematics to find $\theta_1$ and $\theta_2$ $(= \theta_3)$.

The finger-tip position is at ***E***, and the base of the finger starts from ***A***, which coincides with the origin of the rectangular co-ordinate system at ***(0,0)***. For the inverse kinematics, the finger-tip position at ***E*** $(x_E , y_E)$, is knows in terms of the co-ordinate values.

Here,

$AB = l_1 = 55$ mm ; $BD = l_2 = 25$ mm = DE

and $AE = l_4$ (A.1a)

$\angle CBD = \angle FDE$ (A.1b)

Hence, $\angle ABD = \angle BDE$ (A.1c)

Since, $BC = -l_2/(2\cos\sigma)$ so,

AC = $l_1 - l_2/(2Cos\,\sigma)$ ; CE = $l_2 - l_2/(2Cos\,\sigma)$ (A.2)

In ΔACE, $AE^2 = AC^2 + CE^2$

$- 2\,AC.CE.Cos\,(2\sigma - \pi)$ (A.3)

Taking only the negative solution as meaningfully realizable, we have, Substituting ***Cos σ* = *x*** and using (A.1a) and (A.2), in the above equation, we have

$4x^2 = (2xl_1 - l_2)^2 + (2xl_2 - l_2)^2$

$+2(2xl_1 - l_2).\,(2xl_2 - l_2).(\,2x^2 - 1)$ (A.4)

The solution for the above bi-quadratic equation yields the value of $x$ as

$x = \pm[-\,l_2\{(4l_1)^3 - 9(l_1)^2 l_2 + 6\,l_1(l_2)^2 - 4l_1(l_4)^2$

$-(l_2)^3\} + l_1 l_2 + (l_2)^2)]^{1/2}.(4.\,l_1 l_2)$ (A.5)

Taking only the negative solution as meaningfully realizable, we have,

$\sigma = Cos^{-1}\,x$ *thereby,* $\theta_2 = \theta_3 = \pi - \sigma$ (A.6)

*In* ΔACE, $Sin\,\alpha = -(CE.Sin\,2\sigma)/AE$

Using (1a) and (2), in the above equation, we have

$\alpha = Sin^{-1}[\{-l_2\,Sin\,\sigma(2Cos\,\sigma - 1)\}/\,l_4]$ (A.7)

Thence, $\theta_1 = \angle EAX + \alpha$ (A.8)

where , $\angle EAX = \tan^{-1}(y_E / x_E)$ (A.9)