Optimal Control of Grasping Problem Using Postural Synergies

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Abstract. The human hand has a complex musculoskeletal structure which acts as an effective end-effector to perform grasping effectively. Optimal control is a productive method to execute predictive simulations for many biomechanical activities. Optimal control for grasping simulations has been demonstrated for precision grasps for two fingers. However, the procedure to expand it to a full hand is laborious, primarily due to a large computational cost. Furthermore, a full hand performs with a high degree of coordination. These issues can be challenged by the inclusion of kinematic or postural synergies in the multibody framework. In this work, we implement the modelling of kinematic synergies to perform grasping simulations.

Keywords. hand kinematics, postural synergies, grasping, model order reduction

1. Introduction

Grasp path planning is an extensive research area with primary applications in humanoid robotics, industrial ergonomics and also, clinical applications. While the robotics influence aided to formalise grasping concepts of velocity and force transmission, see [1,2], the ergonomics and medical concerns motivated the research to anatomically characterise hand models, see [3,4]. Overall, it also established grasp types from power and precision grasps as defined by Napier [5] to an exhaustive taxonomy, [6]. We have demonstrated two-finger precision grasp examples in [8] with the discrete mechanics and optimal control with constraints (DMOCC, see [7]) approach. Here, a hybrid dynamical system with known switching sequence and unknown switching times was modelled to perform a *reaching* phase and a *grasping* phase in a non-linear optimisation problem. The reaching phase is the prehension phase during which the fingers approach the object surface, and the grasped action is performed during the grasping phase.

While the extension from the two finger model to the complete hand grasping optimal control is modular, the size of the overall optimisation problem increases tremendously. This imposes an enormous computational challenge on the optimiser. Fortu-

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nately, the human hand exhibits a highly coordinated motion due to its complicated underlying musculoskeletal network, see [9]. The coordinated motion has been quantified into eigen modes, called as synergies by Santello in [10]. The concept of synergies arose from a neuroscience perspective where it was observed that the hand motion can be expressed as a linear combination of a basis of a fairly reduced configuration space. Overall, it was observed that the hand can be kinematically operated through a relatively reduced number of degrees of freedom (DoFs). The objective is this work is to implement the kinematic synergies into our multibody grasping framework. Here, we concentrate only on the reaching or prehension phase, so as to only see the viability of using the synergies to be able to close contact as well as possible.

The contribution continues with the description of the multibody model and the inclusion of synergies in Section 2, followed by the results and conclusions in Sections 3 and 4, respectively.

2. Multibody model

The grasping multibody model relies on the joint description, leading to the total number of degrees of freedom. A small introduction is provided on the method of hand postural synergy extraction, followed by the gap closure mechanism.

2.1. Synergy actuated hand model

We describe a rigid body in the director formulation as in [7]. In short, a body is with twelve DoFs with configuration $\boldsymbol{q} = [\,\boldsymbol{\varphi},\,\boldsymbol{d}_1,\,\boldsymbol{d}_2,\,\boldsymbol{d}_3]$, with center of mass $\boldsymbol{\varphi}$ and an orthonomal director triad $\{\boldsymbol{d}_I\}_{I=1,2,3}$. The hand is composed of twenty such rigid bodies connected in a tree like structure through a combination of revolute, cardan and joints with two rotation axes that are non-intersecting and non-orthogonal (nino). With rigid body internal constraints and joint constraints, the model comprises of twenty-six DoFs. These include six DoFs for the wrist is free to move in space and twenty degrees of freedom for the joint angles. The complete structure is depicted in Figure 1. The motion of the hand in time can approximated by through discrete configuration $\boldsymbol{q}_n \approx \boldsymbol{q}\,(t_n)$, i.e. the approximate configuration at time node t_n. To update the configuration from time node n to $n+1$, we apply a discrete nodal reparameterisation

$$\boldsymbol{q}_{n+1} = \boldsymbol{F}_d\,(\boldsymbol{u}_{n+1}, \boldsymbol{q}_n) \tag{1}$$

Here, $\boldsymbol{u}_{n+1}$ represents the increment in the minimal coordinates from time nodes n to $n+1$. The finger digit geometries are modelled as cylinders.

Although there are multiple ways to obtain these eigen grasps, see [11], we focus briefly on the one by Santello, see [10]. Herein, five subjects were made to visualise and mime hand postures for fifty-seven different objects. The joint angles in these poses were captured and a covariance matrix for the captured data was created. Using singular value decomposition, the eigen vectors form the required reduced configuration space or the principal components (PCs), while the corresponding eigen values represented the amount of variance. As per Santello, more than 80% of the posture variance was accounted by the first two PCs. Nevertheless, the study prescribed fifteen PCs, where

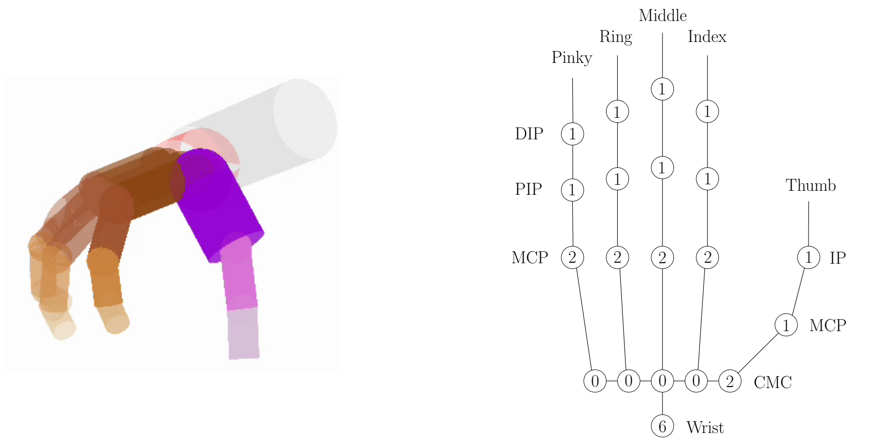

Figure 1. The multibody hand model. Left: the modelling of the digits as cylindrical geometries. Right: the tree structure with the number of DoFs in the circles. The one and two DoF joints are modelled as revolute and cardan (fingers) / nino (thumb), respectively.

the fifteenth eigen value or amplitude was approximately zero. The MATLAB Toolbox *Syngrasp*, see [12], provides a function `SGsantelloSynergies()`, which provides the eigen grasps extracted by Santello in the forms of a matrix $\boldsymbol{S} \in \mathbb{R}^{20\times15}$. Here, the twenty rows prescribe the joint angles while 15 columns represent the eigen vectors or synergies. The matrix $\boldsymbol{S}$ is ordered column-wise, as per their eigen values in the decreasing order. Using a discrete change in the synergies, say $\boldsymbol{z}_{n+1} \in \mathbb{R}^{n_z}$, the increment in the joint angles $\boldsymbol{u}_{n+1}$ can be be calculated using

$$\boldsymbol{u}_{n+1} = \boldsymbol{S}\boldsymbol{z}_{n+1} \tag{2}$$

Consequently, Equation 1 can now be written as,

$$\boldsymbol{q}_{n+1} = \boldsymbol{F}_d\left(\boldsymbol{S}\boldsymbol{z}_{n+1}, \boldsymbol{q}_n\right) \tag{3}$$

2.2. *Gap closure*

A grasp can be assessed through closure properties, namely form and force closures. While form closure would imply as many contact points as degrees of freedom, force closure would suggest lesser contact points, but maintaining the grasp through friction. While such properties can be analysed mathematically, see [2], a coarse way to differentiate between the two is that force closure is ensured through a better contact patch i.e., a tangential contact between the finger and object surfaces. The object to be grasped is described with the configuration $\boldsymbol{q}^O = \left[\boldsymbol{\varphi}^O,\ \boldsymbol{d}_1^O,\ \boldsymbol{d}_2^O,\ \boldsymbol{d}_3^O\right]$. The object surface depends on the configuration $\boldsymbol{q}^O$ and certain dimensions such as radius, length etc. We formulate a contact point $\boldsymbol{\rho}$, which is constrained to lie on the finger digit cylindrical surface. These are, in other words, defined in the digit coordinate system. To close the contact, we define contact closure functions $\boldsymbol{g}$ between the contact point $\boldsymbol{\rho}$ and the object surface, as shown in Figure 2 for a spherical object. For n_c such contact points, we can define an objective

$$J_1 = \sum_{i=1}^{n_c} (\boldsymbol{g}_i^T \boldsymbol{g}_i), \qquad \boldsymbol{g}_i = \boldsymbol{g}_i\left(\boldsymbol{q}, \boldsymbol{q}^O, \boldsymbol{\rho}_i\right) \tag{4}$$

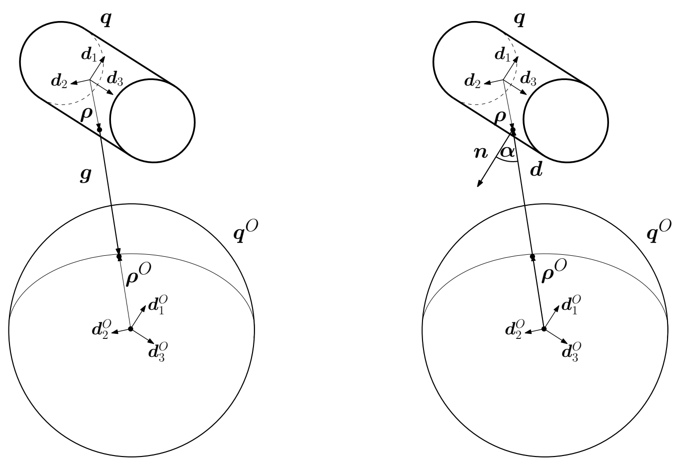

Figure 2. Left: the contact closure condition expressed in Equation 4. Right: the tangential contact condition expressed in Equation 5

The minimisation of J_1 Equation 4 will result in grasp closure with no requirement on relative positional orientation and may also result in partial penetrations. To improve the contact, we calculate the cosine of the angle α between the shortest distance $\boldsymbol{d}$, between the contact point and the object centre, and the normal $\boldsymbol{n}$ to the finger surface at the contact point. Similar to the contact closure condition, we can write the tangential contact objective as,

$$J_2 = \sum_{i=1}^{n_c} \left(1 + \frac{\boldsymbol{d}_i^T \boldsymbol{n}_i}{|\boldsymbol{d}_i| \cdot |\boldsymbol{n}_i|} \right) \tag{5}$$

To achieve gap closure which may lead to proper force closure, it is essential to minimise both objectives J_1 and J_2. Note that, it will require a complete mathematical analysis to ascertain the force closure property of the generated grasps through minimisation and is beyond the scope of this contribution.

3. Results

We perform a two-fold analysis to determine the synergy effectiveness for grasping. Firstly, the grasping simulation is done for the complete hand model. In this model, we impose coordination between the finger interphalangeal joints and the metacarpophalangeal joints among the fingers through constraints, as described in [15]. Secondly, we perform grasping with the synergy based model, wherein the simulation is performed with a varying number of synergies. Assuming, we prescribe N time nodes for the optimisation, for n_z synergy optimisation variables, the number of variables reduces by $(26 - n_z) \cdot N$. The main goal here is to determine the minimum number of synergies that needs to be applied to obtain a good grasp in the sense of minimising J_1 or $J_1 + J_2$ objectives. The grasping simulation is performed for two grasps, namely the prismatic 2-finger grasp, i.e. grasping a cylinder, and the tripod grasp, i.e. grasping a sphere. Both grasps are performed with three contact points, one each on the distal phalanges of the thumb, index and middle fingers.

We implement our grasping simulation framework in the MATLAB environment, by optimising the objective $J = J_1$ or $J = J_1 + J_2$ subject to the kinematic path constraints, specifically Equation 1 for the complete hand model and Equation 3 for the synergy based model. The optimisation is performed with the interior-point optimiser, IPOPT, see [13], with CasADi as a automatic differentiation tool, see [14].

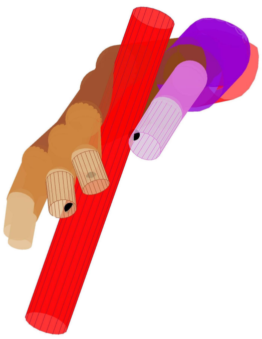

Figure 3. Synergy actuated model ($n_z = 15$) with prismatic 2-finger grasp, see [6], by minimising $J_1 + J_2$ objective. The contact points are shown with ($\bullet$) symbol.

For the prismatic 2-finger example, the resulting grasp posture is shown in Figure 3, with a model actuated through $n_z = 15$ synergies by minimising $J_1 + J_2$ objective. Though the contact is defined for the first three fingers only, we see a coordinated posture for the ring and little fingers as well. We can compare this posture with other models, as shown in Figure 4. In Figure 4 left, we present a grasp posture for a non-synergy actuated model by minimising $J_1 + J_2$ objective. Here, only the index and middle fingers are flexing to close the contact. The ring and little fingers show little flexion at the metacarpophalangeal and interphalangeal joints. In Figure 4 middle, the grasp posture is obtained by only minimising the J_1 objective for a synergy actuated model with $n_z = 15$, due to which we see clear penetration of the three distal phalanges. This posture illustrates the need of the tangential contact objective J_2. We also present the grasp posture obtained with a synergy actuated model with $n_z = 5$ synergies by minimising both $J_1 + J_2$ objectives in Figure 4 right.When comparing the different resulting grasp postures, we can clearly observe the variation in the placement of the contact points. In particular, the inclusion of the tangential contact objective leads to an increased contact area.

The objective values for the synergy analysis is shown in Table 1. It can be observed that the objective value stays at the same order $\left(10^{-12}\right)$ when performing the grasp from 15 synergies to 5 synergies. The values, thereafter till 3 synergies, are still acceptable though higher than 10^{-12}. The optimiser could not obtain solutions with lesser number of synergies. It can be comfortably asserted that this grasping simulation can be performed with 5 synergies while minimising $J_1 + J_2$ objectives. However, when minimising only the J1 objective, we can see that it is possible to obtain gap closure from the last column in Table 1 even with a single synergy.

For the tripod grasp we see a similar grasp performance when the model is actuated with $n_z = 15$ and $n_z = 5$ synergies in Figure 5, left and right respectively, while minimising $J_1 + J_2$ objective. With $n_z = 15$, the index and ring fingers are closer to each other

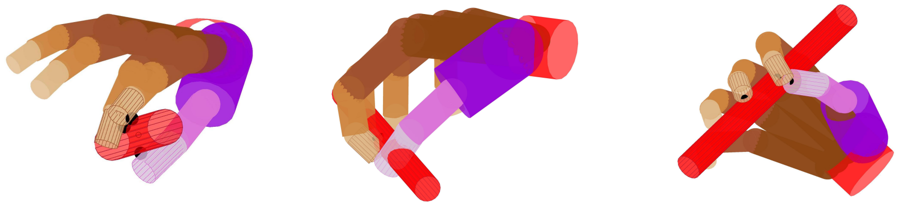

Figure 4. From left to right, we see the grasp posture for prismatic 2-finger grasp with (left) non-synergy actuated model while minimising $J_1 + J_2$ objectives, (middle) synergy actuated model with $n_z = 15$ synergies and only J_1 objective to be minimised and (right) synergy actuated model with $n_z = 5$ synergies while minimising $J_1 + J_2$ objectives. The contact points are shown with ($\bullet$) symbol.

Table 1. Objective values for synergy actuated model with prismatic 2-finger grasp, see [6].

number of synergies	$J_1 + J_2$	J_1	J_2	only J_1
15	-6,06E-14	2,10E-12	-2,16E-12	1,46E-13
14	-2,87E-12	1,04E-12	-3,92E-12	7,01E-14
13	1,31E-11	2,41E-12	-1,55E-11	7,83E-14
12	-1,56E-12	2,23E-12	-3,79E-12	2,17E-13
11	2,00E-12	2,00E-12	-2,11E-15	1,70E-13
10	5,82E-10	2,92E-12	5,79E-10	2,21E-13
9	-1,67E-13	2,79E-12	-2,96E-12	3,01E-13
8	9,89E-12	9,96E-12	-7,04E-14	1,24E-13
7	-4,21E-12	2,91E-12	-7,12E-12	1,29E-13
6	4,63E-12	5,80E-12	-1,17E-12	1,02E-13
5	3,32E-12	6,09E-12	-2,77E-12	4,85E-13
4	8,64E-09	8,65E-09	-1,57E-11	2,40E-12
3	1,06E-05	1,06E-05	2,72E-10	1,29E-13
2				8,93E-14
1				1,18E-13

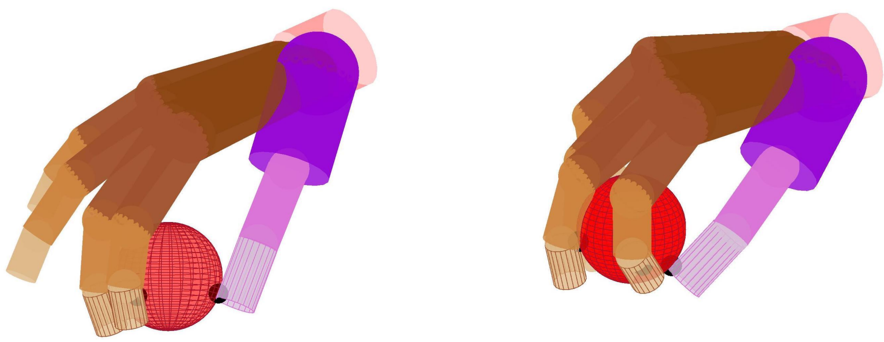

Figure 5. Synergy actuated model with tripod grasp, see [6], with $n_z = 15$ (left) and $n_z = 5$ synergies. The contact points are shown with ($\bullet$) symbol.

as compared to the posture obtained with $n_z = 5$ synergies, which also lead to different contact points. The objective values retains a similar order $\left(10^{-11}\right)$ with even 3 synergies, as seen in Table 2, exhibiting a substantial reduction in the number of actuated

DoFs. Thereafter, it is still possible to obtain solutions with slightly higher objective values while using even a single synergy. As with the previous grasp, it is possible to obtain grasp postures while minimising only J_1 objective for all possible synergy combinations.

Table 2. Objective values for synergy actuated model with tripod grasp, see [6].

number of synergies	$J_1 + J_2$	J_1	J_2	only J_1
15	-2,80E-09	4,03E-13	-2,80E-09	4,13E-13
14	3,49E-13	3,53E-13	-3,77E-15	2,06E-12
13	-3,14E-12	4,79E-14	3,19E-12	1,32E-14
12	-7,05E-11	7,13E-14	-7,06E-11	3,75E-13
11	-1,49E-09	2,58E-13	-1,49E-09	4,76E-12
10	1,81E-12	1,84E-12	-3,20E-14	7,70E-17
9	-3,70E-11	2,98E-14	-3,70E-11	3,38E-13
8	3,35E-10	5,74E-14	3,35E-10	1,38E-12
7	-2,09E-11	1,14E-13	-2,10E-11	9,56E-12
6	2,46E-12	2,45E-12	1,11E-15	3,75E-11
5	-7,85E-11	2,02E-13	-7,87E-11	4,56E-13
4	-3,79E-11	8,45E-13	-3,87E-11	7,12E-13
3	-1,49E-11	1,54E-12	-1,64E-11	2,78E-22
2	1,01E-08	1,01E-08	1,18E-12	2,51E-10
1	2,15E-07	2,15E-07	4,68E-11	6,99E-13

4. Conclusion

We have demonstrated a kinematic grasping methodology with coordinated hand motion achieved through synergies. The grasping performance of the synergy based model has been compared with an independent joint model. The synergy analysis shows the possibility of a significant reduction in the number of independent joint angle DoFs. It also enables the formulation of synergistic actuation torques, as per [16]. This will result in a considerable reduction in problem size when the method is ported to optimal control simulations for grasping where the number of optimisation variables, i.e. DoFs and controls, are multiplied by the number of discrete time nodes. The method, however, is not free from certain drawbacks. In particular, the kinematic hand model is dependent on the description of the synergy matrix and hence is not readily subject to change. For example, the synergy matrix used in this work from *Syngrasp*, does not allow flexion motion for the ring and little finger CMC joints. Also, the thumb CMC joint is modelled as a universal joint in the synergy matrix. Thus, the thumb cannot perform the passive internal rotation motion as observed in human beings. Thus, to add more realism to the grasps, a kinematically appropriate synergy matrix must be used. As an outlook, we plan to include non-interpenetration constraints in our model for the optimal control. The grasps obtained therein will be analysed for force closure properties and their performance will be compared as per grasp quality metrics, as given in [17].

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