# Evaluation of grasp quality measures in real grasps

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***Abstract*—This paper presents the implementation of grasp quality measures in a real-world robotic setup. Specifically, the largest wrench that a grasp can resist due to perturbations in any direction has been computed considering both the actual contact points and the magnitude of the actual grasping forces. The experiments were done using the Allegro Hand with OptoForce tactile sensors and a Fastrak motion tracking system. In this work, the grasp quality measure was experimentally computed using different objects without needing their detailed geometric models, and numerical results are provided.**

***Index Terms*—Grasp quality measures, tactile sensors, real-world implementation, grasp wrench space, multi-fingered robotic hand.**

## I. Introduction

Grasping is vital for robotic manipulation, aiming to fully control an object despite external disturbances, including its own weight. This requires generating internal forces within the object, using complex grippers, such as multi-fingered hands, to ensure stability. Effective grasping is crucial for robotic systems to handle various objects in diverse environments [1].

A grasp quality measure provides a quantitative index to assess grasp effectiveness, using metrics classified into three categories: the location and attributes of contact points, the hand's configuration during the grasp, and a combination of both for a comprehensive quality measure [2].

Numerous studies have proposed various metrics to evaluate grasp quality, but few have been practically implemented and experimentally validated in real-world setups.

For contact point quality measures, the smallest singular value of the grasp matrix $G$, $\sigma_{\min}(G)$, indicates how far the grasp is from a singular configuration, with a larger $\sigma_{\min}(G)$ improving the grasp [3]. The grasp matrix relates fingertip forces to the resultant wrench on the object. Its derivation involves object properties like weight and shape, complicating real-world implementation. To address finger force limitations, the largest resisted wrench measures the maximum external perturbations a grasp can resist in any direction by analyzing the grasp wrench space [4]. This metric requires detailed grasp wrench space analysis, demanding substantial computational resources.

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For hand configuration quality measures, the foundational concepts based on the grasp matrix $G$ are extended to include the hand-object Jacobian $H$. The smallest singular value of $H$ can indicate critical grasp conditions [5]. However, since computing $H$ depends on $G$, this adds complexity to its implementation.

This paper reports the implementation of a widely recognized grasp quality measure, typically confined to planning, in a real-world experimental setup. The contribution lies in translating a theoretical grasp quality metric into a tangible application, to verify its effectiveness and feasibility in actual robotic manipulation tasks. Additionally, the work offers insights into the challenges and considerations essential for real-world scenarios.

## II. Overview of the developed system

In this section, a conceptual overview of the presented system is provided, focusing on the implemented quality measure and the developed software.

### A. Description of the implemented quality measure

The implemented grasp quality measure is the largest resisted wrench, considering finger force limitations to evaluate the maximum perturbation wrench the grasp can resist in any direction [6].

There are two common constraints on the finger forces $f_i$, $i = 1, \ldots, n$. The first constraint is that each finger force magnitude is individually limited, assuming all fingers have the same maximum limit normalized to 1, i.e. $||f_i|| \leq 1$. By approximating the friction cone at each contact point $p_i$ with a pyramid having $m$ edges, each finger force $f_i$ can be expressed as a positive linear combination of primitive forces $f_{ij}$, $j = 1, \ldots, m$. Similarly, the resultant wrench $\omega_i$ at $p_i$ is decomposed into a combination of primitive wrenches $\omega_{ij}$. The combined action of $n$ fingers produces a resultant wrench on the object, given by

$$\omega_0 = \sum_{i=1}^{n} \omega_i = \sum_{i=1}^{n} \sum_{j=1}^{m} \alpha_{ij}\omega_{ij} \quad \text{with } \alpha_{ij} \geq 0, \quad \sum_{j=1}^{m} \alpha_{ij} \leq 1 \tag{1}$$

Considering the variability of $\alpha_{ij}$, the set $\mathcal{P}$ representing the potential resultant wrenches exerted on the object, known as the Grasp Wrench Space (GWS) [7], is the convex hull of the Minkowski sum of primitive wrenches $\omega_{ij}$.

The second common constraint on finger forces is that the sum of their magnitudes is limited, corresponding to a shared power source among all fingers. Assuming a normalized limit of 1, this constraint can be expressed as $\sum_{i=1}^{n} \|f_i\| \leq 1$. Approximating the friction cone with a pyramid as in the previous case, the resultant wrench on the object is:

$$\omega = \sum_{i=1}^{n}\sum_{j=1}^{m} \alpha_{ij}\omega_{ij} \quad \text{with } \alpha_{ij} \geq 0, \quad \sum_{i=1}^{n}\sum_{j=1}^{m} \alpha_{ij} \leq 1 \tag{2}$$

In this context, the set $\mathcal{P}$ is the convex hull of the primitive wrenches $\omega_{ij}$.

The grasp quality measure, accounting for force limitations, is given by the distance from the origin of the wrench space to the closest facet of $\mathcal{P}$ [8]. Geometrically, it corresponds to the radius of the largest ball centered at the origin of the wrench space and entirely enclosed within $\mathcal{P}$, often referred to as the "criterion of the largest ball" [9], i.e.:

$$\mathcal{Q}_{LRW} = \min_{\omega \in \partial\mathcal{P}} ||\omega|| \tag{3}$$

where $\partial\mathcal{P}$ is the boundary of the $\mathcal{P}$. An optimal grasp under one force constraint may not necessarily remain optimal under the other. Figure 1 provides a qualitative depiction of the constraints on finger forces, showcasing the sets of potential wrenches and resultant qualities under each constraint.

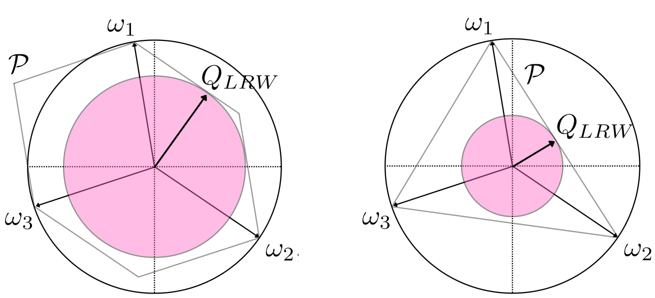


Fig. 1: Qualitative 2-dimensional example of the grasp quality using three fingers and, a) a limit in the module of each force; b) a limit in the sum of the modules of all the applied forces.

The measure $\mathcal{Q}_{LRW}$ holds significant physical interpretation for general-purpose grasps but relies on the chosen reference system for torque computation. Selecting the object's center of mass aligns well with system dynamics, but precise knowledge of it can be challenging. Nevertheless, using a fixed point attached to the object allows to properly compute this grasp quality measure, and so is done in this work. Note that, to compute Euclidean distances in wrench space, a metric adjustment is required and to do it, the torque components are multiplied by a constant $\rho$ with units of $\mathrm{m}^{-1}$.

### *B. Description of the software structure*

The developed software, programmed in C++, computes the grasp wrench space and evaluates grasp quality measures within the Robot Operating System (ROS) framework for an already grasped object. It integrates data from tactile sensors, hand joint position sensors, and position/orientation data from a tracker attached to the grasped object.

The software relies on two key external libraries: Eigen for matrix and vector calculations, ensuring efficient mathematical operations, and Qhull for computing convex hulls, essential for evaluating the grasp quality. Additionally, it utilizes core ROS packages such as *roscpp* for ROS client library functionalities, *sensor_msgs* for standardized sensor message types, and *tf* for managing coordinate transformations between different frames within the robotic system.

Effective communication within the system is facilitated by ROS functionalities for data acquisition and command control, achieved through topics, services, and communication protocols.

## III. Implementation

This section covers the real-world implementation of the developed system, including hardware, implementation details, experimental validation, and challenges across different grasping scenarios.

### *A. Description of the used hardware*

The setup used for implementing the grasp quality measure evaluation includes three primary hardware components: the Allegro Hand, OptoForce sensor, and Fastrak system.

The Allegro Hand by Wonik Robotics Co., is an advanced robotic hand mimicking human dexterity with 16 degrees of freedom (DOF), 4 per finger, actuated by DC motors [10]. Each finger, except the thumb, has one DOF that defines the finger working plane and three for fingertip position and orientation in that plane, while the thumb's first DOF handles the abduction movement. The hand has position encoders to provide precise joint angle feedback, and a real-time PID position control managed by an embedded microcontroller. Communication with a PC is via CAN bus interfaces.

In realistic scenarios, the geometric model of manipulated objects is often partially or entirely unknown, thus, tactile sensors are crucial for recognizing objects and reducing geometric uncertainty [11]. The OptoForce OMD-20-SE-40N tactile sensor measures real-time forces using an optoelectronic principle, where external forces deform optical elements, altering light intensity to photodetectors [12]. Calibration links these signals to physical measurements, enabling contact force sensing during grasping. However, it does not provide torque measurements.

Fastrak, developed by Polhemus Co., is an electromagnetic motion tracking system [13]. Consisting of a transmitter generating low-frequency magnetic fields and a receiver attached to the object being tracked, it precisely monitors positions and orientations in three-dimensional space. The receiver measures the strength and orientation of the magnetic field, enabling calculation of the object's position and orientation relative to the transmitter.

### B. Overview of the implemented procedure

The previously described software structure is adjusted with the available hardware for implementation in a real-world experimental setup, allowing for performance validation. The object is grasped by commanding the hand manually through a GUI or by setting predefined values for specific positions. The real-world implementation is accomplished through the following steps:

- Data Acquisition: The data acquisition process is performed by subscribing to the ROS topics for joint states and OptoForce and using a listener to retrieve *tf* information from the Fastrak.
- Contact Point Computation: When using OptoForce data to determine the contact point position, it is important to understand that the force vector is expressed in a referenced frame located at the base of the spherical structure of the sensor, with a magnitude proportional to the applied force (Figure 2a). By knowing the fingertip position and applying forward kinematics, the contact point position is derived. Besides, the sensor is considered precise only in a limited area close to the fingertip.
  Contact forces measured by the tactile sensor are then expressed in a reference frame attached to the object at the position of the Fastrak receiver, since all points and vectors must be represented in the same reference frame.
- Primitive Wrench Computation: The friction cone is approximated with a pyramid having $m$ edges. Primitive forces aligned with the edges of the pyramid are expressed in a base located at the contact point and given by $\vec{e}_{ki}$, $k = 1, 2, 3$, which are unitary vectors with $\vec{e}_{1i}$ aligned with the measured force $\vec{f}_i$ (Figure 2b). That is:

$$\theta = \tan^{-1}(\mu) \tag{4}$$

$$\alpha = \frac{2\pi}{m} \tag{5}$$

$$\vec{f}_{ij} = \vec{e}_{1i}\cos(\theta) + \sin(\theta)\big(\vec{e}_{2i}\cos((j-1)\alpha) + \vec{e}_{3i}\sin((j-1)\alpha)\big) \tag{6}$$

  where $\mu$ is the friction coefficient, $\theta$ is the corresponding angle of the friction cone, and $\alpha$ is the angle between consecutive primitive forces. By translating $\vec{f}_{ij}$ from each contact point $p_i$ to the point $p_c$ attached to the object, primitive torques $\vec{\tau}_{ij}$ are derived, resulting in primitive wrenches $\vec{\omega}_{ij}$, as:

$$\vec{\tau}_{ij} = \vec{v}_i \times \vec{f}_{ij} \tag{7}$$

$$\vec{\omega}_{ij} = \begin{bmatrix} \vec{f}_{ij} \\ \vec{\tau}_{ij} \end{bmatrix} \tag{8}$$

  where $\vec{v}_i$ is the displacement vector from $p_i$ to $p_c$. Despite potential imprecise contact position readings from the sensor, it is assumed that all primitive forces share the same contact position as the normal force.
- Minkowski Sum for Convex Hull Representation: All combinations of $\vec{\omega}_{ij}$ applied to the object are considered for the used three fingers of the Allegro hand. This includes not only the Minkowski sum of the primitive wrenches for all three fingers but also the combinations involving one and two fingers, covering all scenarios for force limitations for each finger individually, given by

$$\vec{\Omega}_{\text{total}} = \bigoplus_{i=1}^{3} \{\vec{\omega}_{i1}, \vec{\omega}_{i2}, \dots, \vec{\omega}_{im}\} \tag{9}$$

  To address the limitation on the sum of force magnitudes, the union of the three sets of $\vec{\omega}_{ij}$ is considered as:

$$\vec{\Omega}_{\text{total}} = \bigcup_{i=1}^{3} \{\vec{\omega}_{i1}, \vec{\omega}_{i2}, \dots, \vec{\omega}_{im}\} \tag{10}$$

- Grasp Quality Computation: The input points for the convex hull computation are points derived from the wrench vectors $\vec{\Omega}_{\text{total}}$, positioned such that the origin of the convex hull $\vec{x}_0$ corresponds to reference point $p_c$ attached on the object. After calculating the convex hull representing the grasp wrench space, its facets are extracted, along with the normal vectors $\vec{a}_h$ and offsets $b_h$ for each facet with $h = 1, \dots, l$, where $l$ is the number of facets. The distance $d_h$ from the origin to the facet $F_h$ is then computed as:

$$d_h = \|\operatorname{proj}_{\vec{a}_h}(\vec{x}_0 - \vec{x}_h)\| = \frac{|\vec{a}_h \cdot \vec{x}_0 + b_h|}{\|\vec{a}_h\|} = \frac{|b_h|}{\|\vec{a}_h\|} \tag{11}$$

  where $x_h$ is any point in $F_h$. Then, $\mathcal{Q}_{LRW}$ is determined as the distance of the closest facet of the convex hull to the origin as

$$\mathcal{Q}_{LRW} = \min_{h \in \{1,\dots,l\}} d_h \tag{12}$$

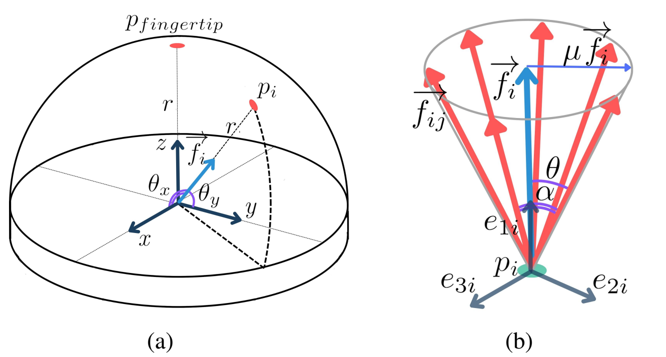


Fig. 2: a) Position of contact point $p_i$ on OptoForce sensor; b) Friction cone and primitive forces for each contact force.

Assuming punctual contacts without friction, the use of three fingers does not allow a Force Closure grasp (note that at least seven points are needed to compute the convex hull in 6D), and thus the grasp quality $\mathcal{Q}_{LRW}$ cannot be computed. Therefore, the quality measure is obtained only for the case of frictional contact points, that introduces the friction and the primitive forces derived from its approximation.

Two cases are assumed regarding the magnitude of the primitive forces. First, all primitive forces are considered unitary to compare the quality measure for different grasps with different contact points, and, second, the actual magnitude of the normal force is used for all its primitives to evaluate the specific grasp quality considering the actual contact points and the magnitude of actual grasping forces.

### *C. Experimental validation*

To validate the performance of the designed system in evaluating grasp quality measures in real-world experiments, several tests were conducted with different objects and grasping models. Using three fingers of the Allegro hand, various configurations were tested to assess the impact of contact positions on the quality measure.

To test the system's adaptability, objects of varying shapes, weights, and materials were used. Material included plastics ($\mu = 0.3$), cartons ($\mu = 0.4$), and Styrofoam ($\mu = 0.5$). The friction cone was approximated with a pyramid of 6 edges and the metric $\rho$ was set to 1.

The Fastrak receiver was attached to a fixed point on each object for accurate comparisons of different grasps.

Table I lists the grasp quality measures for the different scenarios illustrated in Figure 3, in two cases: A) All primitive forces are unitary; and B) each primitive forces has magnitude equal to the actual force applied by that finger. $\mathcal{Q}_{LRW}$ represents the quality measure with individual limitations on each finger force magnitude, while $\mathcal{Q}'_{LRW}$ considers the limitation on the sum of the all finger force magnitudes.

| | **case A** ($\times 10^{-4}$) | | **case B** ($\times 10^{-4}$) | |
|---|---|---|---|---|
| **Grasp** | $\mathcal{Q}_{\mathbf{LRW}}$**(N)** | $\mathcal{Q}'_{\mathbf{LRW}}$**(N)** | $\mathcal{Q}_{\mathbf{LRW}}$**(N)** | $\mathcal{Q}'_{\mathbf{LRW}}$**(N)** |
| **I** | 67.205 | 33.16 | 32.368 | 19.321 |
| **II** | 92.969 | 46.434 | 60.987 | 28.111 |
| **III** | 14.197 | 7.005 | 9.759 | 5.621 |
| **IV** | 24.264 | 12.151 | 17.571 | 10.006 |
| **V** | 14.298 | 7.223 | 5.331 | 3.865 |
| **VI** | 23.303 | 11.722 | 17.764 | 7.091 |
| **VII** | 4.772 | 2.406 | 3.227 | 1.831 |
| **VIII** | 112.039 | 40.875 | 41.317 | 16.214 |
| **IX** | 25.502 | 13.247 | 22.694 | 9.616 |

TABLE I: Quality measures for different grasps.

## IV. Discussion and Conclusion

This paper presents the implementation of the largest wrench that the grasp can resist in any direction as a grasp quality measure, incorporating finger forces limitations in a real-world setup using the Allegro hand with OptoForce tactile sensors. Various grasp scenarios were validated to determine the grasp quality measure through experiments. The experimentation is performed on objects with known materials, regardless of geometry, by fixing the reference point using a Fastrak system.

The Qhull library ensures fast and reliable convex hull computations. However, the OptoForce sensors lack torque

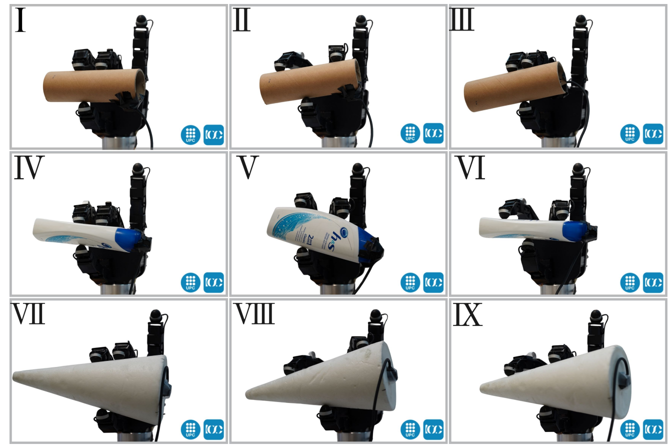


Fig. 3: Different grasp scenarios for three objects: carton, plastic, and Styrofoam, using the Allegro hand, OptoForce sensors, and the Fastrak system.

data and have significant noise regarding force data. Fastrak's magnetic field introduces noise near metallic objects.

Future work will focus on verifying the physical validity of the implemented quality measure, implementing additional quality measures for a comprehensive assessment of grasp quality, and enhancing tactile sensing systems to provide torque data and more reliable force information.

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