DOI: XXX-XXX-XXXX

Performance Indices for the Evaluation of Microgrippers Precision in Grasping and Releasing Phases

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KEYWORDS : Grasping, Microgripper, Microrobotics, Performance indices, Releasing

In manipulating and assembly tasks, the gripper plays a fundamental role. Tasks at the microscale are particularly challenging due to the possible effect of unwanted stiction. Many different grasping tools (generally called microgrippers) have been developed and are described in literature. The differences rely on size, shape, exchanged forces with the manipulated parts and working principle depending on the application field. Despite the large number of research and industrial cases, each author has developed different and not comparable procedures and indices to assess the device grasping and releasing performance. Therefore, the paper proposes a formalization of methods and indices for the evaluation of the performance of a generic contact microgripper in terms of precision in grasping and releasing and successful rate. This review could be helpful to support the design or the choice of the most suitable gripper according to the properties of the components to be manipulated, the task requirements and the system constraints (i.e., according to the application requirements). The validity of the proposed methodologies and indices is confirmed by theory and experimental data analysis.

Manuscript received: August XX, 201X / Accepted: August XX, 201X

1. Introduction

Many efforts have been put in place by the robotic community to define a common methodology and metrics for the assessment of grasping performances. In manipulation research, various initiatives have been carried out to define performance metrics and tests, based on a predefined set of objects, such as the YCB (Yale-CMU-Berkeley) object and model set[1] or the Amazon Picking contest, most of them targeted to dexterous multi-finger grasping of meso or macro scale objects.

At the microscale, while usually the geometry of the manipulated part is quite simple, additional technical challenges arise due to the predominance of superficial over volume forces, which often negatively affect the release phase. A wide variety of microgrippers, usually single or double fingered, has been developed and discussed in the scientific literature, differing in size, shape, exchanged forces, and working principle. Typical examples are tweezers, vacuum pipettes, contact or contactless electrostatic grippers, capillary grippers.

The authors generally present an experimental validation of the proposed solution, including some performance assessment. However, each author adopts different approaches and procedures. The success rate, defined as the percentage of success in grasping and releasing a sample object, usually a microsphere, is reported very often, but very few studies adopt a standardized methodology to define the test. Another aspect which is often investigated is the precision in the grasping and releasing of objects. This aspect is particularly important in the microworld due to the high importance of the adhesive forces (e.g. capillary, van der Waals, electrostatic[2]) with respect to the object weights (Figs. 1 and 2) which often generate sticking effects.

After a brief review of the literature, the paper will focus on the meaning and the definition of accuracy and repeatability proposing a performance assessment of microgrippers in terms of test execution procedure, number of trials, definition and measurement of performance indices (such as accuracy, repeatability), irrespective of the different sources of error. The proposed methodology aims to apply to contact microgrippers (e.g. microtweezers, vacuum or capillary microgrippers) manipulating microcomponents in air in different working condition, in order to assess their performance for various applications.

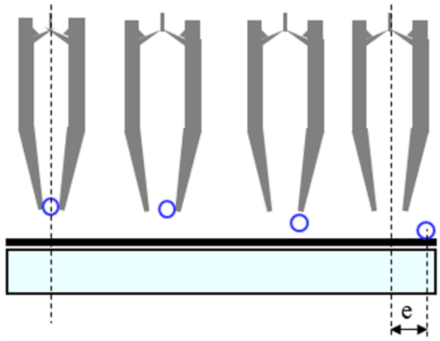

Fig. 1 Example of releasing error due to sticking on a pair of tweezers

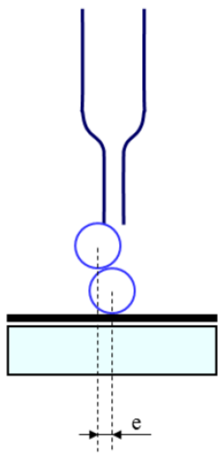

Fig. 2 Example of grasping error, due to sticking, with a vacuum gripper

Finally, for verification purposes, the paper will investigate some practical applications of this methodology, then the conclusions will be drawn.

2. Current Practices in Performance Assessment

Despite the number and variety of works on the development and experimental testing of microgrippers[3-17], only few of them present a precise and quantitative analysis of the gripper performance (Table 1). Most of the authors limit the results to a qualitative analysis based on the observation of the gripper capability to successfully pick and release microcomponents, different in shapes, material and dimensions.

A strategy to study and measure the grasp and release errors in manipulating different microparts was proposed by Dafflon et al[11]. The authors focused on the characterization of the pick and place steps and the method to measure the gripping and releasing errors. The research considered four microgrippers actuated by different working principles: vacuum, microtweezers, inertial microgripper exploiting the adhesion forces, and thermodynamic microgripper for capillary manipulation, and exploiting different types of release strategies.

Very often the tests are performed manipulating microspheres; for example, Chen et al.[3] used borosilicate glass spheres (with a diameter of 7.5-10.9 μm) to verify the release performance of the microgripper. Park et al.[6] report the use of steel beads having diameter smaller than 100 μm in order to test the ability to grip and release objects by frictional force. The manipulation of polystyrene balls (diameter of 50 μm) was considered by Dafflon et al[11]. Chen et al.[10] presented the manipulation of spheres of 100-300 μm by means of a vacuum microgripper. The successful manipulation of polystyrene balls having a diameter of 100-200 μm was demonstrated by Chen et al.[7], but no systematic experimental campaign was carried out. Strategies to manipulate microspheres in air and water were developed by Gauthier et al.[9], exploiting a piezoelectric microgrippers to handle spheres of 100 μm in air, and a microtip to push polystyrene spheres of 50 μm in water. Different microgrippers manipulating polystyrene balls of 50 μm and silicon microcubes with side of 50 μm were analyzed Dafflon et al.[9] Biganzoli et al.[8] used an electrostatic microgripper to manipulate stainless steel microspheres of 300μm and microcylinders with diameter of 400 μm and length of 800 μm. Silicon objects with size of 5×10×20 μm^3 were used by Heriban et al.[4] A wider study was performed by Nah et al.[5] Hand-actuated microtweezers operated on microparts with size in the range of 200-800 μm, whereas using a piezoelectric actuation the gripper grasped and released microparts of size ranging from 100 to 500 μm. Tests were executed on micro watch gears of 500 μm and on a Teflon wire having a diameter of 500 μm.

Only some of the described works present a precise and quantitative analysis of the grasping and releasing tests, whereas most of them just report qualitative results based on the observation of the gripper capability to successfully pick and release microparts[5-7]. Some authors report only the success rate, defined as the percentage of successful operations in the grasping and releasing of microparts with respect to the total number of tests[9-10]. An assembly operation performed by a sequence of 4 steps is considered by Chen et al[10]: tip approaching the target, pick, move towards the final position and place (pick and place). The declared success rate was 85%, whereas the number of tests was not specified.

Another parameter that is sometimes reported is the cycle time necessary to pick and place the object. Heriban et al.[4] analyzed the success rate and the cycle time to perform the pick and place operation (grasp the object from the substrate, move it for 100 μm and release it again on the substrate). The pick and place task was executed 60 times and the time cycle was respectively 3-4 s for the teleoperation and 1.8 s for the automatic cycle.

A few papers report data on the precision of the pick and place task execution calculated with a statistical approach. Dafflon et al.[11] described comparative tests on microtweezers to assess the reliability and the repeatability of the positioning. Positioning repeatability quantified the operation variability in terms of positioning and was calculated as two times the standard deviation of the collected data. Each test was repeated about 30 times. The tests included the positioning repeatability and the percentage of release success. A release was considered correctly performed if the position error was less than 30 μm. The positioning accuracy (the release accuracy) was not considered by Dafflon et al.[11], whereas the repeatability was defined as twice the standard deviation of the position error. Also in this case, the release was considered correct if the positioning error was lower than a predefined threshold.

DOI: XXX-XXX-XXXX

Table 1 Review of the literature

Paper	Type of gripper	Type of objects	No. of trials	Medium	Performance indices
Chen et al. [3], Zhang et al.[12]*	MEMS microgripper with two gripping fingers and a plunging mechanism	Borosylicate spheres (diameter of 7.5-10.9 µm)	200	Air	-Success rate -Releasing accuracy (defined by mean value and standard deviation of the positioning error) -*Releasing time
Heriban et al.[4]	Piezogripper with two independent degrees-of-freedom for each fingers	Silicon objects with size of 5×10×20 µm^3	60	Air	-Success rate -Cycle time
Nah et al.[5]	Microtweezers with two gripping fingers	-Micro watch gears with diameter of 500 µm -Teflon wire with diameter of 500 µm	n/a	Air	Qualitative analysis of the gripper capability
Park et al.[6]	Hybrid-microgripper with two gripping fingers and an integrated force sensor	Steel beads (diameter < 100 µm)	n/a	Air	Qualitative analysis of the gripper capability
Chen et al.[7]	Hybrid-microgripper with two fingers and an integrated vacuum tool	Polystyrene balls with diameter of 100-200 µm	n/a	Air	Qualitative analysis of the gripper capability
Biganzoli et al.[8]	Electrostatic microgripper	-Stainless steel microspheres (diameter of 300µm) -Microcylinders (diameter of 400 µm and length of 800 µm)	n/a	Air	Grasping and releasing precision (defined by mean value and standard deviation of the positioning error)
Gauthier et al.[9]	Piezoelectric microgripper with two fingers	Microspheres (diameter of 100 µm)	n/a n/a	Air Water	Success rate
Gauthier et al.[9]	Pushing microtip	Polystyrene spheres (diameter of 50 µm)	119 97	Air Water	Success rate
Chen et al.[10]	Vacuum microgripper	Spheres (diameter of 100-300 µm)	n/a	Air	Success rate
Dafflon et al.[11]	-Microtweezers -Inertial microgripper -Thermodynamic microgripper -Vacuum gripper assisted by vibration for the release operation	-Polystyrene spheres (diameter of 50 µm) -Silicon cubes (side of 50µm)	30	Air	-Success rate -Positioning (picking and releasing) repeatability (twice the standard deviation of the positioning error)
Rong et al.[13]	Vacuum microgripper with an integrated vibration releasing system	Polystyrene microspheres (diameter of 200 µm)	110	Air	-Success rate -Releasing accuracy (defined by mean value and standard deviation of the positioning error)

The test reported by Chen et al.[3] considered single microspheres that were picked and released for a total of 200 trials. The performance indices were the success rate and the error in the releasing, improperly called "releasing accuracy" in that work, defined by its mean value and standard deviation. The tests included the analysis of the height of the releasing and the effect of the substrate material (steel or glass). In these cases, the substrate did not influence the results. Other results of the same authors are reported[12] that consider the percentage of success, the releasing accuracy, and the releasing time. Biganzoli et al.[8] defined the grasping and releasing performance of the electrostatic microgripper by the mean value and the standard deviation of the positioning error. Finally, Rong et al.[13] presented different experiments on the grasping and releasing of polystyrene microspheres by a vacuum microgripper with an integrated vibration releasing system. The authors reported the success rate and the location accuracy defined as the distance to the target location. They demonstrated that the releasing height affected the location accuracy, showing the suitable values to improve it.

Summarizing, the above discussed analysis of the literature highlights the absence of a standardized approach with regard to: the type of objects to be manipulated, the number of the considered tests (from 30 in Dafflon et al[11] to 700 in Zhang et al.[12]), and the methodology to quantify the precision error.

The present paper aims at filling this gap by proposing standard methodologies and performance indices to assess the manipulation capabilities of microgrippers with different designs, working principles, and size. In more detail, on the basis of the concepts of robot accuracy and repeatability defined by the ISO standard 9283 "Manipulating Industrial Robots – Performance criteria and related test methods" (see Appendix A), this study will define the following indices:

- Grasping or releasing positioning accuracy AC_{xy}.
- Grasping or releasing positioning repeatability RP_{xy}.
- Isotropy index *A* for positioning repeatability.
- Grasping or releasing orientation accuracy AC_{θ}.
- Grasping or releasing orientation repeatability RP_{θ}.

The proposed methodology is easily understandable, describing the most relevant performance parameters, easily applicable to different applications and different setups and based on statistical analysis to keep into account the uncertainness of the process.

3. Definitions and Discussion

The performance of a gripper is influenced by its grasping and releasing precision. When a gripper releases an object, the final object position *P* will be generally different from the desired theoretic position P_0. The releasing error can be defined as the norm of the distance between the two positions:

$$e = ||P-P_0|| \tag{1}$$

If the releasing operation is repeated *n* times, a different position P_i is reached (with i = 1, n) each time. The set of all the attained positions forms a sort of "cloud" as shown in Fig. 3. Therefore, in similarity with the definition of robot accuracy and repeatability provided by the ISO 9283 (see Appendix A), we may define a gripper accuracy and repeatability for grasping and releasing position. Indeed, the ISO9283 can be then significant also for micromanipulation tools[14-15]. Qualitatively, we may define the "repeatability" (RP_{xy}) as the ability of the gripper to release the objects always in the same point, whereas the "accuracy" (AC_{xy}) as the ability to release the object in the correct desired position. The accuracy depends on the effect of constant sources of error, whereas the repeatability depends on the effect of random phenomena. To define these concepts quantitatively, the repeatability will be the measure of the cloud size, and the accuracy will be the distance of the center of the cloud from the target position.

Similarly, if the object shows an orientation, we may also define the accuracy and the repeatability in orientating it (both for the grasping and the releasing).

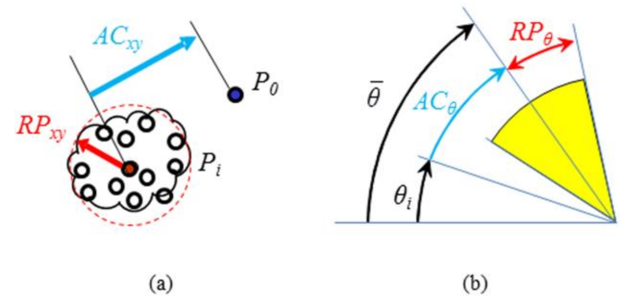

Fig. 3 Accuracy (*AC*) and repeatability (*RP*): a) position (AC_{xy} and RP_{xy}); b) orientation (AC_θ and RP_θ)

The ISO9283 definitions of accuracy and repeatability are based on 3D *xyz* motion, whereas in grasping/releasing we are more interested in 2D *xy* cases. The adaptation is simply performed by discharging the variable *z* from the equations. Moreover, in case of parts with planar geometric features, the angular accuracy and repeatability are calculated only about the *z*-axis.

Such definitions are obviously based on a statistical approach, since the repeatability concept derives from some unknown and random behavior of the system. Indeed, a set of samples of an infinite population of data are analyzed to esteem each parameter. According to the normally accepted heuristic practice, the number of 30 samples was considered sufficient by the standard to represent the whole population with sufficient approximation[18-19].

Nevertheless, as reported in Section 2, different numbers of trials have been chosen so far (from very few to n = 700 by Zhang et al.[12]). It is evident that a deep analysis of the behavior of some phenomena may benefit from a great number of experimental samples, but a practical approach requires to limit the number of experimental data to be collected. The number of n = 30 seems a good compromise for stationary processes, whereas for non-stationary processes the performance varies time to time (effect highlighted by repeating the measurement).

The definition of repeatability is based on statistical data (variability of the distance) rather than maximum distance. Therefore, it is more robust to the presence of low probability outliers.

The definition of repeatability according to ISO9283 suggests that a normal (Gaussian) distribution of the distance *d* was hypothesized although it is stated that the criteria and the methods must be adopted even for other data distribution. The repeatability is based on a range of 3 times the standard deviation (3σ) which guarantees that more that 99% of the data are included (the interval $\pm 2\sigma$ includes about 95%).

It seems however wise to verify that if the error distribution is different, the RP_{xy} definition keeps its meaning and it can be usefully applied. Therefore, two representative theoretical cases (Gaussian distribution, reported in Section 4.1, and Non-Gaussian distribution, reported in Section 4.2) were considered.

The position of the object to be grasped and/or released is indicated by two Cartesian coordinates *x* and *y*, or by its polar coordinates *r* and α (Fig. 4) where *r* can be either positive or negative and α ranges from 0 to 360°; the absolute value of *r* is indicated by *d* which represents the distance from the origin.

We will indicate by $f(\alpha, \bar{\alpha}, \sigma_\alpha)$ a Gaussian distribution of α with mean equal to $\bar{\alpha}$ and standard deviation equal to σ_α.

DOI: XXX-XXX-XXXX

4. Representative Theoretical Cases

Two distributions are here considered and experimental occurrences described. As it will be shown, in some cases, experimental data were suitably described by the Cauchy distribution, instead of by a Gaussian distribution.

4.1 Gaussian Distribution

As first testing case we consider that the distance r is distributed according to a Gaussian centered around 0, with standard deviation σ_r, and that the direction is uniformly distributed with no preferred angle. Therefore, the probability distribution of r is:

$$f_r(r,0,\sigma_r) = \frac{1}{\sigma_r\sqrt{2\pi}}\exp\left(-\frac{1}{2}\left(\frac{r}{\sigma_r}\right)^2\right) \quad -\infty < r < \infty \tag{2}$$

However, while defining repeatability, we are interested in the absolute distance of the object from the origin then we must consider the distribution of $d = |r|$ (Fig. 5a)

$$f_d(d,\sigma_r) = \frac{2}{\sigma_r\sqrt{2\pi}}\exp\left(-\frac{1}{2}\left(\frac{d}{\sigma_r}\right)^2\right) \quad 0 \le d < \infty \tag{3}$$

In this case, the mean value for d and its standard deviation are:

$$\bar{d} = \int_0^\infty d\ f_d(d,\sigma_r)\,dd = \sqrt{\frac{2}{\pi}}\sigma_r \cong 0.798\sigma_r \tag{4}$$

$$\sigma_d = \sqrt{\int_0^\infty \left(d-\bar{d}\right)^2 f_d(d,\sigma_r)\,dd} = \sqrt{\frac{\pi-2}{\pi}}\sigma_r \cong 0.603\sigma_r \tag{5}$$

and the repeatability will be:

$$RP_{xy} = \bar{d} + 3\sigma_d \cong 2.606\sigma_r \tag{6}$$

It was calculated that, in this case, the probability that one point falls inside a circle of radius RP_{xy} is about 99.1%, whereas if the repeatability is strictly defined as $RP2 = \bar{d} + 2\sigma_d$, the probability is 96.5%.

The probability that one point has the coordinate x and y results:

$$f_{xy} = \frac{f_d(d,\sigma_r)}{2\pi d} \quad \text{with} \quad d = |r| = \sqrt{x^2+y^2} \tag{7}$$

Therefore, the distribution of the probability error on x (or y) can be evaluated as (see Fig. 5b):

$$f_x = \int_{-\infty}^{+\infty} f_{xy}\,dy \quad \text{and} \quad f_y = \int_{-\infty}^{+\infty} f_{xy}\,dx \tag{8}$$

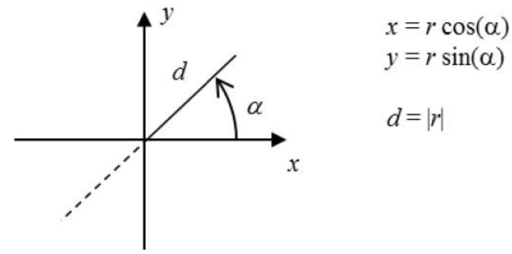

Fig. 4 Definition of the distance d. The origin of the axes is the center of the clouds of points ($\bar{x}$ and $\bar{y}$ in Eq. (A2))

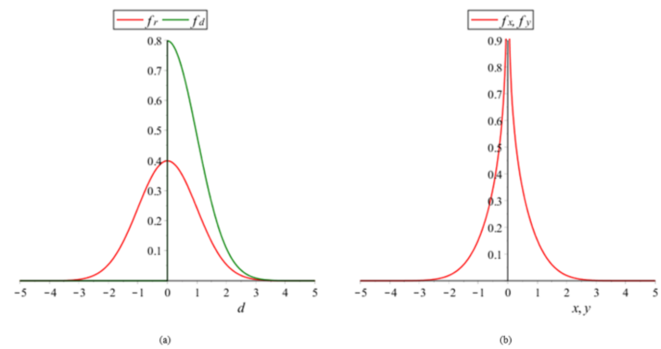

Fig. 5 Distribution of: (a) the distance d; (b) its x and y components in the case of Gaussian distribution of d $\left(d = |r| = \sqrt{x^2+y^2}\right)$

4.2 Non-Gaussian Distribution

As second testing case, we consider the case in which the x and y errors are normally distributed as:

$$f(x,\bar{x},\sigma_x) = \frac{1}{\sigma_x\sqrt{2\pi}}\exp\left(-\frac{1}{2}\left(\frac{x-\bar{x}}{\sigma_x}\right)^2\right) \tag{9}$$

$$f(y,\bar{y},\sigma_y) = \frac{1}{\sigma_y\sqrt{2\pi}}\exp\left(-\frac{1}{2}\left(\frac{y-\bar{y}}{\sigma_y}\right)^2\right) \tag{10}$$

Since we are interested in the distance d which is insensitive to rotations around the center of its distribution, we consider x and y as principal axes and we can assume that x and y are uncorrelated; therefore the covariance is null ($\sigma_{xy} = 0$). In this case, the distribution of the distance d is no longer Gaussian. For example, for $\sigma = \sigma_x = \sigma_y$, $\bar{x} = \bar{y} = 0$, it results (Fig. 6):

$$\begin{aligned} f'(d,\sigma) &= \int_{\alpha=0}^{2\pi} d\ f\left(d\cos\alpha,0,\sigma\right) f\left(d\sin\alpha,0,\sigma\right) d\alpha = \\ &= \frac{d}{\sigma^2}\exp\left(-\frac{1}{2}\left(\frac{d}{\sigma}\right)^2\right) \end{aligned} \tag{11}$$

The mean value of the distribution is:

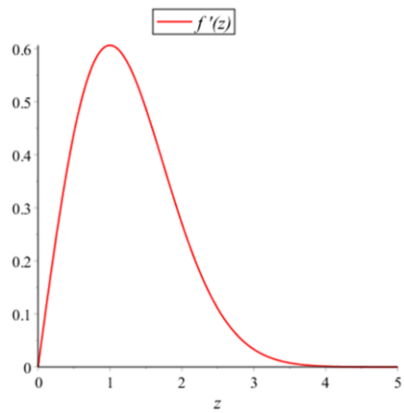

Fig. 6 Distribution of *f'(z)* (normalized distribution of *f'*(d, σ)) of the distance $z = d/\sigma$ with $d = \sqrt{x^2 + y^2}$ when x and y are normally distributed with standard deviation σ

$$\bar{d} = \frac{\sqrt{2\pi}}{2}\sigma \cong 1.253\sigma \quad (12)$$

and its standard deviation is:

$$\sigma_d = \frac{\sqrt{8-2\pi}}{2}\sigma \cong 0.655\sigma \quad (13)$$

Therefore, the repeatability will be:

$$RP_{xy} = \bar{d} + 3\sigma_d \cong 3.219\sigma \quad (14)$$

which corresponds to a probability of more than 99.4% of d being $0 \leq d \leq RP_{xy}$. Analogously, considering *RP2*, it is possible to show that the probability decreases but still is more than 96%.

If we consider that the error on x and y are Gaussian distributed with different standard deviations σ_x and σ_y, the distribution of d changes. Table 2 summarizes some cases with σ_{max} = max(σ_x, σ_y), σ_{min} = min(σ_x, σ_y), and $k = \sigma_{min}/\sigma_{max}$; k = 1 corresponds to the case of Fig. 6, and since the direction does not influence d, the case k = 0 is equivalent to the case of Fig. 5.

We may conclude that in all the analyzed cases the distance RP_{xy} corresponds to the value containing more than 99% of the samples.

Table 2 Example of computation of the repeatability indices and their probability in different cases of Non-Gaussian Distribution

Case	1	2	3	4
σ_x	1	1	1	1
σ_y	0	1/3	2/3	1
k	0	1/3	2/3	1
$\bar{d}$	0.798	0.889	1.055	1.253
σ_d	0.603	0.567	0.576	0.655
RP_{xy}	2.606	2.589	2.783	3.219
$P(RP_{xy})$	99.1%	99.0%	99.2%	99.4%
RP2	2.004	2.023	2.207	2.564
P(RP2)	95.5%	95.4%	96.0%	96.3%

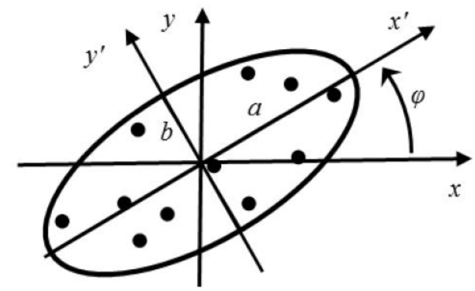

Fig. 7 Example of anisotropy behavior along a generic direction; equivalent ellipses defining the uncertainty area

It's worth to note that the above analysis is based on the distance d, which is not affected by rotations around the center, then the results do not change if the distribution is observed along rotated axes (e.g. Figs. 7 and 8).

4.3 Repeatability Anisotropy

The proposed index RP_{xy} gives a general value for the repeatability without highlighting the possible anisotropy of the errors that can be present in some cases as, for instance, in Figs. 7 and 8.

The experience shows that the uncertainty area of the grasping/releasing errors are often roughly similar to ellipses or circles. Therefore, the uncertainty ellipses associated to the covariance matrix Σ can be considered representative of the phenomena:

$$S^T \Sigma^{-1} S = h^2 \quad (15)$$

with

$$S = \begin{bmatrix} x - x_0 \\ y - y_0 \end{bmatrix} \qquad \Sigma = \begin{bmatrix} \sigma_x^2 & \sigma_{xy} \\ \sigma_{xy} & \sigma_y^2 \end{bmatrix}$$

where h is a suitable scale factor.

The covariance matrix is

$$\Sigma = \begin{bmatrix} \sigma_x^2 & \sigma_{xy} \\ \sigma_{xy} & \sigma_y^2 \end{bmatrix} = \begin{bmatrix} a^2\cos(\varphi)^2 + b^2\sin(\varphi)^2 & (a^2 - b^2)\cos(\varphi)\sin(\varphi) \\ (a^2 - b^2)\cos(\varphi)\sin(\varphi) & a^2\sin(\varphi)^2 + b^2\cos(\varphi)^2 \end{bmatrix} \quad (16)$$

where $a \cdot h$ and $b \cdot h$ are the semi-axis of the ellipses and φ is the orientation of the semi-axis whose length is $a \cdot h$.

If σ_{xy} = 0 the axes of the ellipses are parallel to the Cartesian axes x, y, and the semi-axes of the ellipses are $a \cdot h = \sigma_x$, $b \cdot h = \sigma_y$.

For h = 1, it is possible to prove that the semi-axes a and b are the square root of the eigenvalues of Σ, and that the direction of the axes are represented by the associated eigenvectors U_a and U_b:

$$U_a = \begin{bmatrix} \cos(\varphi) \\ \sin(\varphi) \end{bmatrix} \qquad U_b = \begin{bmatrix} -\sin(\varphi) \\ \cos(\varphi) \end{bmatrix}$$

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We can assume, as isotropy index A for positioning repeatability, the ratio between the minimum and the maximum axis length which corresponds to the square root of the inverse of the conditioning number of Σ

$$A = \frac{\min(a,b)}{\max(a,b)} \tag{17}$$

where A = 1 indicates a perfect isotropy and A = 0 a perfect anisotropy. The semi-axes are generally the square root of the eigenvalues of the covariance matrix; when the covariance σ_{xy} is null, the ellipse axes are parallel to the axis of the reference system and may be simply determined as $a = \sigma_x$ and $b = \sigma_y$. Obviously the isotropy index is not assessed for the orientation repeatability.

5. Analysis of Experimental Data

In this section, representative experimental cases are analyzed by applying the theory developed in the previous sections. Some preliminary results have been discussed by Ruggeri et al.[20]

5.1 Experimental Source 1

Fig. 8 presents the data described in the experimental campaign presented by Chen et al.[3]. The release process shows an anisotropic behavior along x and y directions. Indeed, the value of σ_x is 0.16 µm, whereas σ_y is 0.84 µm and σ_{xy} is almost null and in this case all the points are included in an ellipse whose axes are $2\sigma_x$ and $2\sigma_y$. If we evaluate the repeatability in the x-y plane adopting the definitions of Eqs. (A4) and (A6), we get $\bar{d} = 0.68$ µm, σ_d = 0.47 µm, RP_{xy} = 2.1 µm. The isotropy index is:

$$A = \frac{\min(\sigma_x, \sigma_y)}{\max(\sigma_x, \sigma_y)} = 0.19 \tag{18}$$

being $\sigma_{xy} = 0.0039 \approx 0$.

The different indices are graphically visualized in Fig. 8. The circle marked "*RP*" has a radius equal to RP_{xy}, whereas the dashed circle marked as "*RP2*" has a radius equal to $\bar{d} + 2\sigma_d$. The other circles have radius equal to σ_d, $2\sigma_d$, $3\sigma_d$. The smallest ellipse has semi-axis sizes equal to $2\sigma_x$ and $2\sigma_y$, while the axes of the biggest ellipse are $3\sigma_x$ and $3\sigma_y$. In this specific case, all the points are inside the circle with radius equal to *RP2* that theoretically corresponds to a probability of about 95%, but the adoption of RP_{xy} foresees the theoretically worst performance of the system with a probability of about 99%.

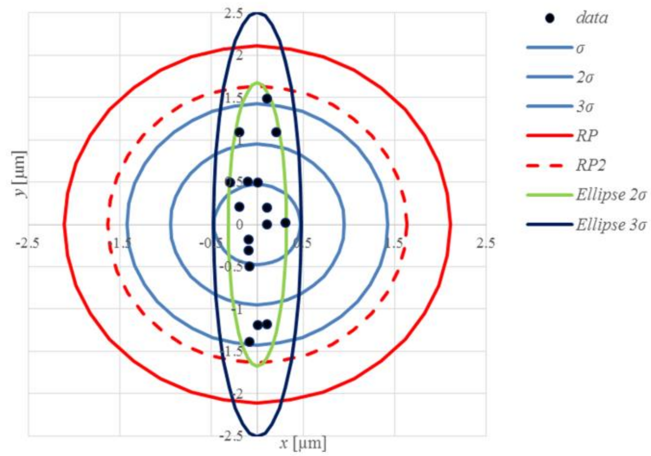

Fig. 8 Performance indices calculated for n = 16 trials performed with glass beads of diameter = 10 µm

5.2 Experimental Source 2

As second case (Fig. 9) we may consider the tests presented by Fontana et al.[15] The data are more randomly distributed along the x and y axis, as showed by the shape of the ellipses. The value of σ_x is 0.13 mm, whereas σ_y is 0.15 mm and σ_{xy} is 0,0004 ≈ 0 mm^2. Evaluating the repeatability, we get $\bar{d} = 0.16$ mm, σ_d = 0.1 mm, RP_{xy} = 0.47 mm. The isotropy index A is 0.9, meaning that the distribution is almost isotropic.

5.3 Experimental Source 3

Fig. 10 reports the case of 120 releases of a sphere with a diameter of 800 µm, carried out on the same set-up at STIIMA lab by Fontana et al.[15] The two circles have radius respectively equal to RP_{xy} (red circle named *RP*) and *RP2*. The statistical distribution of the experimental data is best represented by the Cauchy distribution.

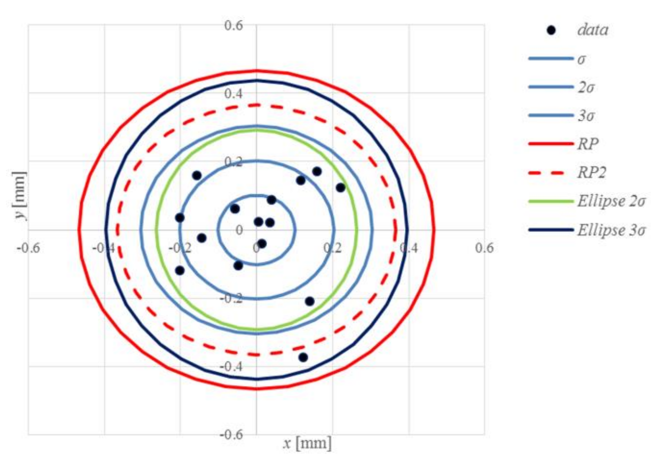

Fig. 9 Performance indices calculated for n = 16 trials performed with metal spheres of diameter = 300 µm

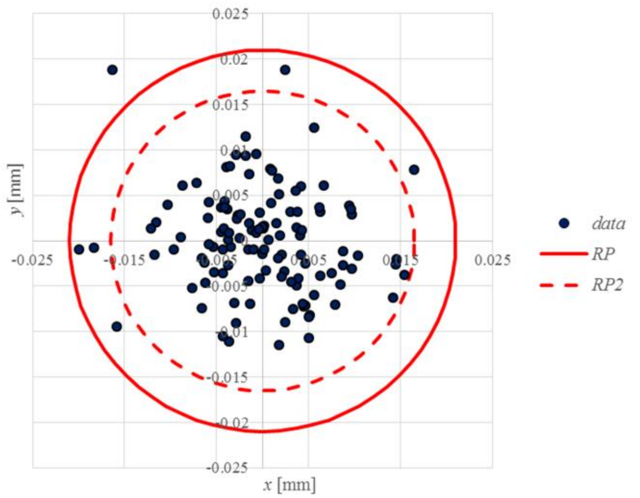

Fig. 10 Performance indices calculated for n = 120 trials performed with spheres of diameter = 800 μm

A point was outside the *RP* circle and 5 points were between the two circles. Therefore, 95% were inside the inner circle and 99.2% were inside the outer one.

This example shows that exceptionally few experimental points could be worse than the predicted value of the repeatability. Indeed, the repeatability is based on a statistical concept rather than a deterministic one. However, this statistical definition makes the index more robust with respect to outliers.

The other main parameters of the data were:

$\sigma_x = 0.0067$ mm
$\sigma_y = 0.0057$ mm
$\sigma_{xy} = -4.5\ 10^{-6}\ \text{mm}^2 \approx 0$
$A = \sigma_y / \sigma_x \approx 0.85$

The test proved that also in this case, with distribution different from the Gaussian one, the repeatability of the process was well represented by the proposed index RP_{xy}.

5.4 Experimental Source 4

Fig. 11 describes a typical anisotropic error distribution of a set of data collected during further tests executed with the set-up at STIIMA lab. The circle has the radius equal to RP_{xy}, whereas the ellipse represents the uncertainty area defined on 3σ basis. The parameters that describe the error distribution are:

$\sigma_x = 2.671$ mm
$\sigma_y = 1.710$ mm
$\sigma_{xy} = -3.533$ mm
$\sigma_d = 2.439$ mm
$d = 2.018$ mm

$RP_{xy} = 9.335\ \text{mm} \approx 3\ \max(a,b)$

Indeed, the semi-axes of the ellipses (1σ) are:

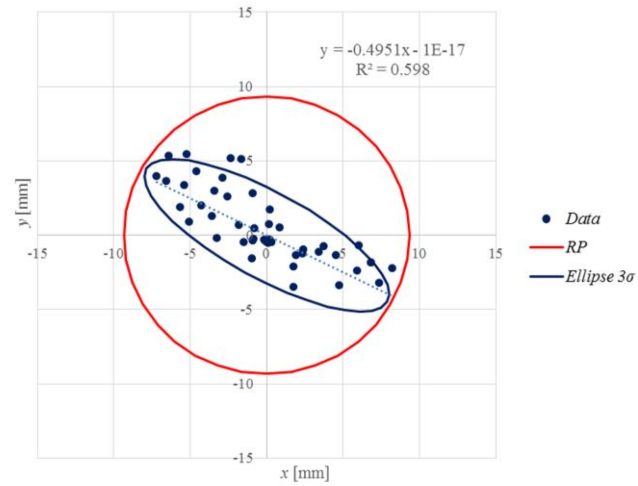

Fig. 11 Performance indices calculated for n = 104 trials performed with spheres of diameter = 500 μm

$a = 3.022$ mm
$b = 0.958$ mm
$A = b/a = 0.317$

The proposed indices RP_{xy} and A were also applied to other experimental data and they gave a good estimation of the global repeatability of the system[21].

6. Discussion of the Results

The theoretical and experimental analysis described in the previous sections confirms that the proposed set of indices, based on the concepts of robot accuracy and repeatability, can be used to assess the microgripper releasing and grasping performance, namely:

- Grasping or releasing positioning accuracy AC_{xy} defined in accordance to (A1).
- Grasping or releasing positioning repeatability RP_{xy} defined in accordance to (A3).
- Isotropy index A for positioning repeatability as defined by (17).
- Grasping or releasing orientation accuracy AC_θ as defined by (A7).
- Grasping or releasing orientation repeatability RP_θ as defined by (A8).

However, to guarantee the consistency of the collected data with the declared performance indices, it is also necessary to define the conditions in which data have to be collected and processed and keep the related parameters constant.

The proposed methodology requires a number of trials n = 30, as suggested to assess repeatability and accuracy.

The performance of the gripper is influenced by the whole workcell characteristics, the test component (shape, size, mass,

DOI: XXX-XXX-XXXX

material, etc.), substrate, gripper movements, release height, and the external parameters (e. g. temperature, humidity), then they depend on the specific application. In the case the test component shape does not allow an unambiguous definition of its orientation, the orientation accuracy and repeatability have not to be calculated. Concerning the test component, the proposed methodology could rely on the DIN standard 32563 (Production equipment for microsystems – System for classification of components for microsystems), that provides a classification system for microcomponents and microsystems in manipulation tasks.

Obviously, the measuring system must have an accuracy value much lower than the expected performance indices of the gripper; the ISO9283 suggests an accuracy less or equal to 25% of the value to be certified.

The data must be collected and processed in the following order.

For the grasping:

1. An object must be present in the grasping area
2. The counter i is set to zero ($i = 0$)
3. The counter is increased by 1 ($i = i+1$)
4. The $x_a y_a$ position of the object is measured
5. The manipulator is moved over the object (coordinates $x_a y_a z_a$)
6. The object is grasped with the appropriate procedure depending on the gripper characteristics; if necessary, the gripper is moved back to $x_a y_a z_a$
7. The $x_b y_b$ position of the object is measured
8. The $x_i y_i$ position error is evaluated as $x_i = x_b - x_a$, $y_i = y_b - y_a$
9. If $i < n$, the object is released in a predefined area, a new object (with the same characteristics) must be made available in the grasping area and the process starts again from step 3
10. If $i = n$, the test is completed and the data are analyzed according to the predefined procedure.

For the releasing:

1. The counter i is set to zero ($i = 0$)
2. The counter is increased by 1 ($i = i+1$)
3. The manipulator is moved to the grasping area, an object is grasped, the manipulator is moved to a predefined $x_a y_a z_a$ position
4. The $x_a y_a$ position of the object is measured
5. The object is released with the appropriate procedure depending on the gripper characteristics
6. The $x_b y_b$ position of the object is measured
7. The $x_i y_i$ position error is evaluated as $x_i = x_b - x_a$, $y_i = y_b - y_a$
8. If $i < n$, the process starts again from step
9. If $i = n$, the test is completed and the data are analyzed according to the predefined procedure.

The releasing and the grasping tests can be combined in an unified test by measuring both errors in the same cycle; in this case, after measuring the grasping error, before releasing the object and measuring the corresponding error, the gripper must be moved to a different position to simulate the effect of a real working cycle.

The success of the grasping or releasing operation must be declared as the ratio between the number of valid operations and the number of attempts.

7. Conclusions

The paper has addressed the fundamental issue of assessing micro gripper performance.

After a critical review of the different approaches adopted in literature, the authors have proposed a methodology to evaluate the grasping and releasing performance of a generic contact microgripper, derived from the definition of robot accuracy and repeatability, and independent from the microgripper typology and robot architecture. The proposed method is based on the statistical analysis of the cloud of points that represent the actually achieved poses of the manipulated objects and includes also an isotropy index, to take into account anisotropic distributions. Four different data sets, resulting from different test cases, are critically discussed, highlighting the usefulness of the proposed indices. Although this does not prove to be a general result to different situations, it seems that these indices could be proposed for further investigation and verification. Finally, a procedure is proposed towards a standardization of the testing procedures for microgrippers. It is expected that the methodology could be also applicable to contact-less microgrippers or microgrippers operating in liquid media.

ACKNOWLEDGEMENT

This work was partially supported by Regione Lombardia under the Accordo Quadro CNR - Regione Lombardia.

Appendix A

A.1 Position Accuracy and Repeatability According to ISO9283

The ISO standard 9283 (Manipulating Industrial Robots – Performance criteria and related test methods) is the principal document for the definition of the performance assessment of a generic industrial robot in geometrical positioning, since 1982. It describes the methods to assess many performance indices which report about static or dynamic quantities, although it is not mandatory to investigate all of them.

Among several different performance indices, the ISO9283 standard defines the positioning and orientation (pose) accuracy and repeatability of the end-effector.

The repeatability of a robot is defined as its ability to achieve the same pose repeatedly, therefore it measures the variability of the obtained poses. On the other hand, accuracy is the difference (i.e. the error) between the commanded poses and the achieved ones.

According to the standard, to measure the position accuracy and repeatability, the execution of a position command is repeated n = 30 times and the corresponding achieved poses are recorded; the collected data are then analyzed. We indicate by x_0, y_0, and z_0 the commanded position, and by x_i, y_i, and z_i the position attained at the i-th repetition.

The accuracy is defined as:

$$AC = \sqrt{(x_0 - \bar{x})^2 + (y_0 - \bar{y})^2 + (z_0 - \bar{z})^2} \qquad \text{(A1)}$$

with

$$\bar{x} = \frac{1}{n}\sum x_i \qquad \bar{y} = \frac{1}{n}\sum y_i \qquad \bar{z} = \frac{1}{n}\sum z_i \qquad n = 30 \qquad \text{(A2)}$$

where $\bar{x}$, $\bar{y}$ and $\bar{z}$ represent the barycenter of the attained positions. The repeatability is defined as follows:

$$RP = \bar{d} + 3\sigma_d \qquad \text{(A3)}$$

with

$$\bar{d} = \frac{1}{n}\sum d_i \qquad \text{(A4)}$$

$$d_i = \sqrt{(x_i - \bar{x})^2 + (y_i - \bar{y})^2 + (z_i - \bar{z})^2} \qquad \text{(A5)}$$

$$\sigma_d = \sqrt{\frac{\sum (d_i - \bar{d})^2}{n-1}} \qquad \text{(A6)}$$

where d_i is the distance of the i-th attained position from the barycenter of the attained positions, and σ_d is the esteemed standard deviation.

The standard clarifies that the number n of the repetitions to be used is exactly n = 30, and that the defined method must be used even if the distribution is not normal (Gaussian).

Furthermore, specific operating and environmental testing conditions are required, e.g. the pose values have to be stable before recording them and the testing temperature has to be 20±2 °C.

A.2 Angular Accuracy and Repeatability

Being an angle θ representative of a one-dimensional orientation and being θ_0 the commanded orientation and θ_i the achieved orientation at the i-th repetition, the angular accuracy and repeatability are defined by:

$$AC_\theta = \bar{\theta} - \theta_0, \quad \text{with} \quad \bar{\theta} = \frac{\sum \theta_i}{n} \qquad \text{(A7)}$$

$$RP_\theta = 3\sigma_\theta \qquad \sigma_\theta = \sqrt{\frac{\sum (\theta_i - \bar{\theta})}{n-1}} \qquad \text{(A8)}$$

For a three-dimensional orientation the accuracy and repeatability have to be calculated for the three orientations. Again, the number n of repetitions must be n = 30, and (A3) and (A8) must be used even when the distribution is not normal.

A.3 Notes on Repeatability

It is possible to see that the repeatability for the position and orientation errors are computed in different ways, cf. (A3) and (A8). The reason is that the orientation error is represented by a single value that can be positive or negative with zero mean value. In contrast, the position error depends on the square root of the sum of the squares of the error on x and y (and z considering a spatial case).

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