DRAFT NIST Special Publication 1229

**Proposed Standard Terminology for
Robotic Hands and Associated
Performance Metrics**

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This is a working document from a NIST led working group under the Institute of Electrical and Electronics Engineers (IEEE) Robotic Hands Grasping and Manipulation (RHGM) Technical Committee with periodic updates based on public comment. It serves as an archive for future community consensus based standards development work. Opportunities to comment on this document will be announced using robotics community portals such as rhgm.org and robotics-worldwide. Comments should be communicated using the robot-performance@nist.gov mail list (see <https://email.nist.gov/mailman/listinfo/robot-performance> to sign up). Use "Terminology" as the subject line when submitting comments for this document. All comments are subject to release under the Freedom of Information Act (FOIA).

Abstract

1 Increasing the flexibility and general-purpose applicability of robots are longstanding goals
2 for many application domains. Several avenues of research addressing these goals in-
3 clude robotic hand mechatronic design, sensing, and control. Inspired by nature, these
4 end-effectors hold potential for allowing robots to grasp and manipulate a broader range
5 of objects without requiring customized end-of-arm tooling or grippers. With the rapidly-
6 growing number and diversity of robot hands, there is a need to quantify their individual
7 capabilities and characteristics under a unified framework. Terminology and associated
8 definitions are needed in order to support this performance measurement framework. Ter-
9 minology that is agreed-upon by the stakeholders will facilitate communication among
10 individuals involved in the research, design, and integration of robotic hands through a
11 common and consistent lexicon. Furthermore, common terminology will improve com-
12 munication with end-users, instilling effective matching of technology capabilities with
13 end-user requirements.

14
15 This publication proposes a draft set of definitions as a means of stimulating discussion
16 among researchers, developers, integrators, and end-users of robotic hands. This draft
17 document may one day provide input to a consensus standard on terminology for robotic
18 hands. Resources, in addition to existing standards, such as industry terminology lists may
19 be leveraged by contributors to this document with appropriate reference.

Key words

20
21 Grasping; Manipulation; Performance Metrics; Robotic Hands; Terminology.
22

23

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39 1. Scope

40 1.1 General

41 This set of terminology and associated definitions consists of terms associated with robotic
42 hands. A common and consistent lexicon, this terminology will facilitate communication
43 between individuals involved in the research, design, and integration of robotic hands, in-
44 cluding but not limited to, robotic systems to support the manufacturing, health-care, and
45 service industries. The terminology covers terms relevant to defining the performance for
46 robotic hands.

47 1.2 Resources

48 To harmonize the terminology with current field practice, definitions have been drawn from
49 the literature or other public sources when possible [1][2]. Related or relevant terms defined
50 in existing International Standards Organization (ISO) standards are referenced in order
51 to build on consensus definitions and avoid duplication. For additional detail, such as
52 associated illustrations, these as well as additional standard terms can be accessed on-line¹.
53 In other instances, definitions have been derived while developing this document. Instances
54 of multiple definitions are also documented with the longer-term intentions of using this
55 document as the starting point to develop industry consensus-based standards to support
56 the characterization of robotic hands.

57 1.3 Technology Coverage

58 This set of terminology is designed to be applicable to robotic hands with three or more
59 fingers. A robotic hand is defined to be an integrated system of mechatronics, sensors,
60 and control algorithms with considerable variability in the number of degrees of actuation,
61 degrees of freedom (DOF), and joint types. Furthermore, a robotic hand may be equipped
62 with a touch sensing technology such as, but not limited to, fingertip embedded six-axis
63 load cells, pressure-sensitive tactile sensors, vision-based contact sensing, and bio-inspired
64 impedance tactile sensing capable of resolving point of contact, shear, and normal forces.

65 2. Definitions

66 2.1 Convention Used in Definitions

- 67 • "[]" signifies the source of the definition.
- 68 • Note: are notes as they appear in the referenced standard.
- 69 • Discussion: documented comments from the community and the authors of this re-
70 port.

¹ISO Online Browsing Platform (OBP): www.iso.org/obp/ui#search

71 2.2 General

72 **actuator**, n – power mechanism used to effect motion of fingers or wrist

73 Note: Example of actuators used in robotic hands: electric motor, electromagnetic actuator,
74 electric static actuator, pneumatic actuator, hydraulic actuator, ultrasonic motor, rubber
75 actuator, shape memory alloy, piezoelectric actuator, multi-material fluidic actuators
76 *[from ISO 14539:2000(E/F)]*

77 **clamping element**, n – part of finger or finger link specially designed for direct contact to
78 objects
79 *[from ISO 14539:2000(E/F)]*

80 **finger**, n – kinematic chain structure whose first joint is fixed on the palm

81 Note: A finger may make direct contact to objects. A finger moves primarily with respect
82 to the palm.
83 *[from ISO 14539:2000(E/F)]*

84 **fully-actuated hand**, n – robotic hand(s) that provide individual actuation to all degrees of
85 freedom of the fingers
86 *[NIST defined]*

87 **grasp**, n – constraints of an object by a robotic hand's fingers or palm
88 *[from ISO 14539:2000(E/F)]*

89 **grasping**, v – motion to apply constraints by finger(s) or palm to an object
90 *[from ISO 14539:2000(E/F)]*

91 **grasping safety**, n – function to avoid insecure grasps
92 *[from ISO 14539:2000(E/F)]*
93 [Discussion:](#)

- 94 1. Propose renaming the term to be "secure grasping" to avoid safety implications which
95 would relate to collaborative robot standards.

96 **secure grasping**, n, function to avoid insecure grasps or damage to part being grasped

97 **object**, n – A solid (non-fluid) body, grasped or manipulated by a robotic hand
98 *[derived from ISO 14539:2000(E/F)]*
99 [Discussion:](#)

- 100 1. The object may be rigid or non-rigid.

101 **palm**, n – base member of hand to which the fingers are connected
102 *[NIST defined] [from ISO 14539:2000(E/F)]*
103 [Discussion:](#)

104 1. Alternative definition is
105 **palm**, n - solid member in the basic mechanical structure of a hand on which the first
106 joints of fingers are fixed
107

108 2. Note: A palm may make direct contact with objects [from ISO 14539:2000(E/F)]

109 **Power transmission mechanism**, n – mechanism for transmitting the driving power from
110 the actuators to the fingers

111 Note: Example of power transmission mechanisms used in robotic hands: linkage transmis-
112 sion, wire transmission, gear transmission, screw transmission, cam transmission, spring
113 transmission, fluid/pneumatic transmission, direct actuation

114 [ISO 14539:2000(E/F)]

115 Discussion:

116 1. This could be extended to include actuation of the wrist.

117 **Power transmission mechanism**, n - a mechanism for transmitting the driving power
118 from the actuators to the fingers, or wrist, if applicable.

119 **release**, n – removal of a robotic hand’s fingers or palm constraints from an object
120 [NIST defined]

121 **releasing**, v – motion to eliminate constraints from an object
122 [from ISO 14539:2000(E/F)]

123 **robot interface**, n – interface (mechanical or electrical) of a robotic hand to the interfaces
124 of robots

125 [derived from ISO 14539:2000(E/F)]

126 Discussion:

127 1. A proposed alternative is
128 **robot interface**, n - location of interfaces for connections between a robotic hand
129 and the robot. The connections may form attachment points and provide interfaces
130 for communications, electronics, and power

131 **sensor**, n – device for acquiring, from the robotic hand and/or objects, signals to be used
132 for controlling the gripper in object handling

133 [derived from ISO 14539:2000(E/F)]

134 **soft robotics**, n – the specific subfield of robotics dealing with constructing robots from
135 highly compliant materials, similar to those found in living organisms

136 [from https://en.wikipedia.org/wiki/Soft_robotics, Accessed: June 2018]

137 **state**, n – condition of constraints of an object and resulting pose of the object
138 *[from ISO 14539:2000(E/F)]*

139 **under-actuated hand**, n – robotic hand with fewer actuators than degrees of freedom
140 *[NIST defined]*

141 **degrees of freedom**, n – number of independent parameters that fully define the kinematic
142 configuration of a mechanical system
143 *[NIST defined]*

144 **degrees of actuation**, n – number of independent actuators used to control a mechanical
145 system's degrees of freedom. Typically, the degrees of actuation are less than or equal to
146 the degrees of freedom.
147 *[NIST defined]*

148 **wrench**, n – force-torque vector applied to a rigid body.
149 *[NIST defined]*

150 **2.3 Grasps**

151 **cage**, n – a pre-grasp state where fingers are positioned around an object prior to making
152 contact with an object
153 *[NIST defined]*
154 Discussion:

- 155 1. Note that there are many definitions of "cage" in the literature. E.g.,
156 "A cage is a configuration of the manipulator that bounds the mobility of the objects"
157 "To cage an object is to bound its mobility....caging provides a way to control an
158 object without immobilizing it....a cage might constitute a useful waypoint to the
159 [immobilizing] grasp." *from [3, 4]*

160 **external grasp**, n – grasp that effects on the external surface of the object
161 *[from ISO 14539:2000(E/F)]*
162 Discussion:

- 163 1. All surfaces are external, otherwise you could not contact them. Proposed rewrites:
164 **external grasp**, n - grasp on an object through flexion or adduction of fingers. See
165 definitions for flexion and adduction.
166 or
167 **external grasp**, n - grasp that effects only on the outermost surface(s) of the object

168 **adduction**, n – motion towards centerline of hand such that angles between fingers decrease
169

170 **flexion**, n – motion that decreases the angle between a finger segment and its proximal
171 segment

173 **form closure grasp**, n – grasp with degrees of freedom of object being 0 or less without
174 considering friction forces at contact points
175 *[from ISO 14539:2000(E/F)]*

176 **force closure grasp**, n – grasp with degrees of freedom of object being 1 or more without
177 considering friction forces at contact points but 0 or less with considering them
178 *[from ISO 14539:2000(E/F)]*

179 Discussion:

180 1. Can degrees of freedom can be fewer than 0? If you have negative degrees of free-
181 dom, you are over-constrained. For instance, you can fully constrain an object with 2
182 fingers, but if you have 5 fingers on the object, you are over-constraining it, making
183 it have negative DoF.

184 2. Proposed new definitions by NIST:

- 185 • Grasp that can resist any externally applied wrench on the object by an appropri-
186 ate combination of finger forces applied at the respective finger-object contact
187 locations. [5]
- 188 • A grasp is in force-closure if the fingers can apply, through the set of contacts,
189 arbitrary wrenches on the object, which means that any motion of the object is
190 resisted by the contact forces . [6]
- 191 • A grasp is in form-closure if the location of the contact points on the object
192 ensures its immobility. [7]

193 **grasp planning**, v – determining the grasp positioning of a hand with respect to an object
194 such that the grasp is theoretically force-closed
195 *[NIST defined]*

196 **grasp quality metrics**, n – metrics that calculate the degree of force-closure for a prospec-
197 tive grasp. Related to grasp planning
198 *[NIST defined]*

199 **inside grasp**, n – see internal grasp
200 *[from ISO 14539:2000(E/F)]*

201 **internal grasp**, n – grasp that effects on the internal surface of the object
202 *[from ISO 14539:2000(E/F)]*

203 Discussion:

204 1. This refers to a grasp that effects only on the internal surface of the object, such as
205 picking up a ring by extending two fingers so that they maintain contact with the
206 interior diameter.

207 2. Proposed re-write:
208 **internal grasp**, n - grasp on an object achieved through extension or abduction of
209 fingers.

210 **abduction**, n – motion away from centerline of hand such that angles between fingers
211 increase

212

213 **extension**, n – motion that increases the angle between a finger segment and its proximal
214 segment

215

216 **outside grasp**, n – see external grasp
217 *[from ISO 14539:2000(E/F)]*

218 **power grasp**, n – a grasp characterized by large areas of contact between the grasped object
219 and the surfaces of the fingers and palm and by little or no ability to impart motions with
220 the fingers

221 *[NIST defined based on Cutkosky 1989] [2]*

222 Discussion:

223 1. This grasp is utilized when considerations of stability and security of grip are pre-
224 dominant.

225 **precision grasp**, n – a grasp where the object is held with the tips of fingers
226 *[NIST defined based on Cutkosky 1989] [2]*

227 Discussion:

228 1. This grasp is utilized with smaller objects or when more grasp degrees of freedom
229 are required.

230 2.4 Fingers

231 **degrees of mobility of finger**, n – dimensions of the moving space of a finger
232 *[from ISO 14539:2000(E/F)]*

233 Discussion:

234 1. Use figure to provide parameters for space? Possibly include as a metric? Is this
235 referring to Cartesian space

236 **degrees of freedom of finger**, n – minimum number of inputs which can determine the
237 configuration of a finger
238 *[from ISO 14539:2000(E/F)]*

239 **multi-joint finger**, n – finger with two or more joints
240 *[adapted from ISO 14539:2000(E/F)]*

241 **rotational finger**, n – finger that makes rotational motions
242 *[from ISO 14539:2000(E/F)]*
243 [Discussion:](#)

244 1. Discussion: Rotation with respect to what axis?

245 **translational finger**, n – finger that makes translational motions
246 *[from ISO 14539:2000(E/F)]*

247 **fully-actuated finger**, n – finger with individual actuation to all degrees of freedom
248 *[NIST defined]*

249 **under-actuated finger**, n – finger with fewer actuators than degrees of freedom
250 *[NIST defined]*

251 2.5 Forces

252 **contact force**, n – force exerted from a finger to an object through a contact point, contact
253 line, or contact plane
254 *[from ISO 14539:2000(E/F)]*

255 **grasp force**, n – magnitude of the sum of the contact forces on an object
256 Note: The forces and moments exerted on the object other than the contact forces include
257 external gravitational and inertial forces.
258 *[derived from gripping force in ISO 14539:2000(E/F)]*

259 **manipulating force**, n – vector sum of all contact forces exerted from fingers to an object
260 *[from ISO 14539:2000(E/F)]*

261 2.6 Sensing

262 **object presence detection**, n – detection of object presence, used in the following situa-
263 tions:

- 264 (a) to make sure the object to be grasped is properly placed;
- 265 (b) to make sure the object is successfully grasped;
- 266 (c) to make sure the object is successfully released

267 *[derived from ISO 14539:2000(E/F)]*

268 Discussion:

- 269 1. Note that this definition does not assume that presence detection is via contacting or
270 non-contacting sensors.

271 **finger position sensing**, n – sensing of the finger position, used in the following situations:

- 272 (a) the finger control (such as servo control) needs the finger position information;
273 (b) the object size or shape is measured by grasping

274 *[derived from ISO 14539:2000(E/F)]*

275 **grasping force sensing**, n – sensing of the grasp force exerted on objects in the following
276 situations:

- 277 (a) grasp force is specified, e.g., in handling of fragile objects;
278 (b) finger joints are controlled for stable grasps

279 Note: grasping force can be sensed with a force sensor or from the finger actuating current
280 *[derived from gripping force sensing in ISO 14539:2000(E/F)]*

281 **slip detection**, n – sensing of slip between fingers and objects in the following situations:

- 282 (a) to avoid grasping and lifting objects that are too heavy;
283 (b) to avoid loose and unstable grasps of objects;
284 (c) to grasp objects with a minimum force necessary to avoid slips

285 *[derived from ISO 14539:2000(E/F); origination ISO 8373]*

286 **tactile sensing**, n – extrinsic sensing near the surface of fingers or palm with the following
287 modalities:

- 288 (a) spatial position of contact location
289 (b) normal and shear contact force
290 (c) high-frequency mechanical transients
291 (d) temperature

292 *[NIST defined]*

293 **proprioceptive sensing**, n – intrinsic sensing within the phalanges or palm of hand with
294 the following modalities:

- 295 (a) joint or finger position
296 (b) joint or finger force or torque

297 *[NIST defined]*

298 2.7 Control

299 **force control**, n – control scheme in which only the force is commanded

300 *[from ISO 14539:2000(E/F)]*

301 Discussion:

- 302 1. The force being controlled could be that exerted on the object or the force at the
303 fingertips, depending on the algorithm.

304 **grasp stability** (1), n – state in which an object restores its initial pose in the gripper after
305 its position is slightly changed as a result of disturbance forces applied to it

306 *[from ISO 14539:2000(E/F)]*

307 **grasp stability** (2), n – state in which the gripper fingers always keep contact with the
308 object it is grasping without slippage when the object is exposed to disturbance

309 *[forces; from ISO 14539:2000(E/F)]*

310 **hybrid control**, n – control scheme in which the position commands and force commands
311 on the task coordinate system are transformed into those on the joint coordinate system and
312 are integrated through a formula of conversion so that the joint coordinate servo control is
313 performed

314 *[from ISO 14539:2000(E/F)]*

315 **impedance control**, n – control scheme in which only the position commands and the
316 force commands are integrated through real or virtual equations of motion so that the task
317 coordinate servo control is performed

318 *[from ISO 14539:2000(E/F)]*

319 Discussion:

- 320 1. Consider rewording definition-

321 **impedance control**, n - control scheme in which only the position commands are
322 issued to the controlled system with selectable stiffness or damping properties so
323 that the task coordinate servo control is performed

324 **in-hand manipulation**, n – the ability to change the pose of an object using only the fingers
325 while within the grasp of a robotic hand

326 *[NIST defined]*

327 **two-value control**, n – control scheme in which the command is either “open” or “close”

328 *[from ISO 14539:2000(E/F)]*

329 **position control**, n – control scheme in which only the position is commanded

330 *[from ISO 14539:2000(E/F)]*

331 Discussion:

332

333 1. This could be joint, fingertip, or part position that is commanded. The coordinate
334 system being used will depend on what item is being commanded.

335 **velocity control**, n – control scheme in which only the velocity is commanded
336 *[from ISO 14539:2000(E/F)]*

337 Discussion:

338 1. This could be joint, fingertip, or part velocity that is commanded. The coordinate
339 system being used will depend on what item is being commanded.

340 2.8 Coordinate systems

341 Discussion:

342 1. It is desirable to identify which coordinate frames should be defined with respect to
343 robotic hands, e.g., with respect to the palm, wrist, or other.

344 2. Determine the benefits of standardizing coordinate systems and motion nomencla-
345 tures for robotic systems, see ISO 9787. In the literature, there are several variations
346 in use and even different robot manufacturers choose to use their own method, despite
347 the existence of ISO 9787.

348 **world coordinate system**, n – stationary coordinate system referenced to earth which is
349 independent of the robot motion, denoted by O0-X0-Y0-Z0
350 *[from ISO 14539:2000(E/F) ; origination ISO 8373 and ISO 9787]*

351 **base coordinate system**, n – coordinate system referenced to the base mounting surface,
352 denoted by O1-X1-Y1-Z1
353 *[from ISO 14539:2000(E/F); origination ISO 8373 and ISO 9787]*

354 **mechanical interface coordinate system**, n – coordinate system referenced to the me-
355 chanical interface, denoted by Om-Xm-Ym-Zm
356 *[from ISO 14539:2000(E/F) ; origination ISO 8373 and ISO 9787]*

357 Discussion:

358 1. Could clarify "mechanical interface" to be "mechanical interface by which the hand
359 is attached to the robot arm"

360 **tool coordinate system**, n – coordinate system referenced to the tool of the end effector
361 attached to the mechanical interface, denoted by Ot-Xt-Yt-Zt
362 *[from ISO 14539:2000(E/F) ; origination ISO 8373 and ISO 9787]*

363 Discussion:

364 1. Need to clarify meaning of tool in this context. Is it a tool held by the end effector,
365 which in our case is the hand? Or is it used in the traditional sense to mean the hand?

366 2. if we use the term end effector in this document, we should define it as we mean it.

367 **task coordinate system** n – coordinate system referenced to the site of the task, denoted
368 by $O_k-X_k-Y_k-Z_k$
369 *[from ISO 14539:2000(E/F) ; origination ISO 8373 and ISO 9787]*

370 **object coordinate system**, n – coordinate system referenced to the object, denoted by O_j-
371 $X_j-Y_j-Z_j$
372 *[from ISO 14539:2000(E/F) ; origination ISO 8373 and ISO 9787]*

373 **perception system coordinate system**, n – coordinate system referenced to the perception
374 sensor which monitors the site of the task, denoted by $O_p-X_p-Y_p-Z_p$
375 *[derived from ISO 14539:2000(E/F); origination ISO 8373 and ISO 9787]*

376 **tool center point (TCP)**, n – point defined for a given application with regard to the me-
377 chanical interface coordinate system (as defined in ISO 8373)
378 *[derived from camera coordinate system in ISO 14539:2000(E/F)]*

379 2.9 Performance Measures

380 **benchmarking**, v – process that compares measurements against established goals, oper-
381 ating targets, and performance expectations
382 *[NIST defined]*

383 **finger force tracking**, n – control of force trajectory exerted by a finger on an external
384 surface

385 Note: This capability is particularly important for many state-of-the-art robotic grasping
386 and manipulation control algorithms that use force-based control approaches. Moreover,
387 this capability can be used for touch-based grasp planning, controlled interaction for texture
388 discrimination and object localization.

389 *[from NIST SP on robotic hand performance] [8]*

390 **finger strength**, n – the maximum force a robotic fingertip can impose on an external sur-
391 face while at full extension.

392 Note: This measure relates to the overall strength of the hand during grasping or manipu-
393 lation.

394 *[from NIST SP on robotic hand performance] [8]*

395 **grasp cycle time**, n – the minimum time required for a robotic hand to achieve full closure
396 from a known pre-grasp configuration and to return to the pre-grasp configuration from the
397 grasp position

398 Note: This measure yields information regarding a hand's closing/opening speed capabilities.
399

400 *[from NIST SP on robotic hand performance]* [8]

401 **grasp efficiency**, n – the hand's ability to efficiently modulate grasp force in the presence
402 of exogenous disturbance forces applied to the object

403 Note: This measure will yield a hand's control and sensing capabilities regarding slip minimization and operational efficiency in grasping objects with uncertain disturbance loads.

404 *[from NIST SP on robotic hand performance]* [8]
405

406 **grasp strength**, n – the maximum force a robotic hand can transmit through an object from
407 grasping it

408 Note: This measure provides information regarding a hand's payload capabilities for various object sizes as well as its limits in resisting pulling or pushing forces during a grasp operation.

409 *[from NIST SP on robotic hand performance]* [8]
410

411 **in-hand manipulation**, n – robotic hand's ability to control the pose of an object within its
412 grasp
413

414 Note: The pose of an object is described in Cartesian coordinates, and the manipulation efficacy is captured in terms of control error between the desired object Cartesian pose and the measured object Cartesian pose over a time-varying trajectory. This capability is arguably one of the most difficult to achieve and measure, but is paramount to achieving dexterous robotic systems.

417 *[from NIST SP on robotic hand performance]* [8]
418

419 **kinematic measure**, n – in grasping, a measure concerned with evaluating positions, velocities, or accelerations of palms, fingers, points of contact, or parts under grasp

420 *[NIST defined]*
421

422 **kinetic measure**, n – in grasping, a measure used to evaluate force, torques, and any other measure of effort such as electrical current

423 *[NIST defined]*
424

425 **object pose estimation**, n – measure of how well a robotic hand can estimate the pose of an object

426 Note: The pose of an object is described in Cartesian coordinates, and the estimation fidelity will be captured in terms of the error between the hand-estimated Cartesian pose versus the reference-measured Cartesian pose. Object pose estimation is useful feedback for in-hand manipulation control and hand-arm coordination and control, particularly since visual occlusions for an external vision system typically occur when grasping an object.

428 *[from NIST SP on robotic hand performance]* [8]
429

430 **slip resistance**, n – measure of a robotic hand's ability to resist slippage of an object within
431

its grasp

Note: Slip resistance factors in the friction properties of the hand.

[from NIST SP on robotic hand performance] [8]

touch sensitivity, n – measure of the smallest contact force exerted by a robotic finger on an external surface

Note: This measure provides information on a hand's ability to delicately interact with minimal disturbance to the immediate environment as well as detect small force perturbations. Direct applications would include touch-based grasp planning, or part acquisition with object location or shape uncertainties.

[from NIST SP on robotic hand performance] [8]

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