(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
18 March 2021 (18.03.2021)

WIPO | PCT

(10) International Publication Number
WO 2021/048598 A1

(51) International Patent Classification:
B25J 9/16 (2006.01)

(21) International Application Number:
PCT/IB2019/057734

(22) International Filing Date:
13 September 2019 (13.09.2019)

(25) Filing Language: English

(26) Publication Language: English

(71) Applicant: **OMRON CORPORATION** [JP/JP]; 801, Minamifudodo-cho, Horikawahigashiiru, Shiokoji-dori, Shimogyo-ku, Kyoto-shi, Kyoto, 600-8530 (JP).

(72) Inventors: **VON DRIGALSKI, Felix**; c/o OMRON SINICX Corporation, Nagase Hongo Building 3F, 5-24-5, Hongo, Bunkyo-ku, Tokyo-to, 113-0033 (JP). **TANIGUCHI, Shohei**; c/o University of Tokyo, Graduate School of Engineering, 3F, 7-3-1 Hongo, Bunkyo-ku, Tokyo-to, 113-0033 (JP). **SHIBATA, Yoshiya**; c/o OMRON Corporation, 801, Minamifudodo-cho, Horikawahigashiiru, Shiokoji-dori, Shimogyo-ku, Kyoto-shi, Kyoto, 600-8530 (JP). **IJIRI, Yoshihisa**; c/o OMRON Corporation, 801, Minamifudodo-cho, Horikawahigashiiru,Shiokoji-dori, Shimogyo-ku, Kyoto-shi, Kyoto, 600-8530 (JP).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*
— *in black and white; the international application as filed contained color or greyscale and is available for download from PATENTSCOPE*

(54) Title: IN-HAND POSE ESTIMATION

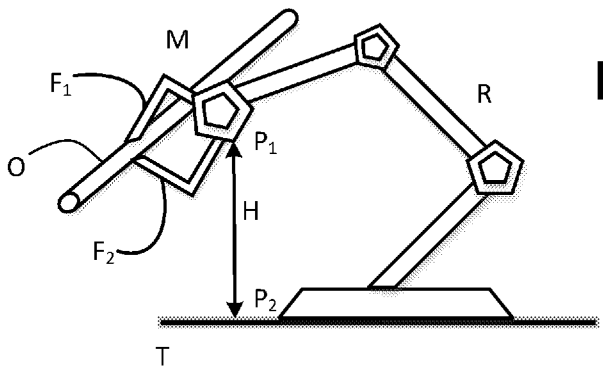


Fig. 4

(57) Abstract: It is provided a method (and corresponding entity, computerprogram, system, medium) for determining the in-hand pose ofan object held by a robot. The method comprises the steps of:- moving, in an environment, a hand of the robot holdingan object;- estimating, at a given time instant, an in-hand posewith which the robot is holding the object based on earlierinteraction information, the earlier interaction informationincluding position information indicating a hand position atan earlier time instant, and interaction status informationindicating whether the robot has interacted with anenvironment reference element at the earlier time instant,wherein the earlier time instant is a time instant precedingin time the given time instant.

WO 2021/048598 A1

In-hand pose estimation

FIELD OF THE INVENTION

The present invention relates to a method (and corresponding entity, computer program, system, medium) for determining an in-hand pose of an object held by a robot.

TECHNICAL BACKGROUND

For robotic assembly, especially the autonomous ones, estimating the pose of a grasped object is an important requirement and task. For instance, in a peg-in-hole insertion task, the robot should know the pose of the peg in its hand precisely in order to know the relative position and pose between the peg and the hole; once this is known, then the robot can insert the peg into the hole easily using, for instance, forward/inverse kinematics and impedance control. However, in many cases, uncertainty by noisy measurement in grasped pose estimation (as well as also the tolerance in the robot positioning, wear in the gripper’s grasping surfaces, links and joints as well as other perturbations) causes failures in subsequent manipulation tasks. Also, prior art techniques often rely on computationally complex models to perform such a task, or on a number of information about the robot and/or the environment that are not always available or easy to obtain, thus decreasing the reliability of and repeatability in performing the task, and increasing the setup cost.

SUMMARY OF THE INVENTION

One of the objects of the invention is to improve the prior art solutions and/or overcome some of the problems encountered in prior art solutions.

According to a first aspect of the invention, it is provided a method for determining an in-hand pose of an object held by a robot, the method comprising the steps of moving, in an environment, a hand of the robot holding an object; estimating, at a given time instant, an in-hand pose with which the robot is holding the object based on earlier interaction information, the earlier interaction information including position information indicating a hand position at an earlier time instant, and interaction status information indicating whether the robot has interacted with an environment reference element at the earlier time instant, the earlier time instant being a time instant preceding in time the given time instant.

Optionally, in the method of the first aspect of the invention, the position information indicates a plurality of hand positions at respective earlier time instants, and the status interaction information indicates whether the robot, in correspondence of said respective earlier time instants, has interacted with the environment reference element.

Optionally, in the method of the first aspect of the invention, the earlier interaction information includes interaction status information indicating that the robot has interacted with the environment reference element at least at one earlier time instant.

Optionally, in the method of the first aspect of the invention, the earlier interaction information comprises interaction status information indicating that the robot has interacted with the environment reference element at least at two, preferably at least three, earlier time instants, and the position information indicates the hand position at the corresponding at least two, and respectively three, interaction time instants.

Optionally, in the method of the first aspect of the invention, estimating the in-hand pose comprises determining a posterior probability of the in-hand pose based on the earlier interaction information.

Optionally, in the method of the first aspect of the invention, estimating the in-hand pose comprises calculating the in-hand pose based on $p\left(x \middle| \{y_t, c_t\}_{t=1}^{T}\right)$, wherein x represents the in-hand pose, c_t the pose of the hand, and y_t indicates whether the robot has interacted with the environment reference element.

Optionally, in the method of the first aspect of the invention, the posterior probability of the in-hand pose is determined using a particle filter method.

Optionally, in the method of the first aspect of the invention, the posterior probability of the in-hand pose is determined on the basis of:

$$\frac{1}{N}\sum_{i=1}^{N} p\left(y_T \middle| x_{T-1}^{(i)}, c_T\right)$$

Optionally, in the method of the first aspect of the invention, the particles of the particle filter method are updated based on an interaction status information for a given particle.

Optionally, the method of the first aspect of the invention includes: estimating, at a further earlier time instant preceding in time the earlier time instant, the in-hand pose on the basis of information that is different from information depending on interaction with the environment.

Optionally, in the method of the first aspect of the invention, the estimating at the further earlier time instant includes estimating the in-hand pose on the basis of predetermined hand position information given in advance, and/or sensor information indicating an interaction between the hand and the object.

Optionally, in the method of the first aspect of the invention, estimating the in-hand pose includes estimating the in-hand pose on the basis of a model of the object, wherein the model of the object is preferably a geometrical model.

Optionally, in the method of the first aspect of the invention, the interaction status information is determined on the basis of sensor modality information.

Optionally, in the method of the first aspect of the invention, the interaction status information is based on the output of one or more amongst a force-torque sensor, a tactile sensor, an image sensor, a 3D sensor.

According to a second aspect of the invention, it is provided an entity (200) for determining an in-hand pose of an object held by a robot, the entity comprising: a movement controller (210) for causing the hand of the robot to move in an environment, while the hand is holding an object; a processor (220) configured to estimate, at a given time instant, an in-hand pose with which the robot is holding the object based on earlier interaction information, the earlier interaction information including position information indicating a hand position at an earlier time instant, and interaction status information indicating whether the robot has interacted with the environment reference element at the earlier time instant, the earlier time instant being a time instant preceding in time the given time instant.

Optionally, in the entity (200) of the second aspect of the invention, the position information indicates a plurality of hand positions at respective earlier time instants, and the status interaction information indicates whether the robot, in correspondence of said respective earlier time instants, has interacted with the environment reference element.

Optionally, in the entity (200) of the second aspect of the invention, the earlier interaction information includes interaction status information indicating that the robot has interacted with the environment reference element at least at one earlier time instant.

Optionally, in the entity (200) of the second aspect of the invention, the earlier interaction information comprises interaction status information indicating that the robot has interacted with the environment reference element at least at two, preferably at least three, earlier time instants, and the position information indicates the hand position at the corresponding at least two, and respectively three, interaction time instants.

Optionally, in the entity (200) of the second aspect of the invention, the processor (220) is configured to estimate the in-hand pose by determining a posterior probability of the in-hand pose based on the earlier interaction information.

Optionally, in the entity (200) of the second aspect of the invention, the processor (220) is configured to estimate the in-hand pose by calculating the in-hand pose based on

$$p\left(x \middle| \{y_t, c_t\}_{t=1}^{T}\right),$$

wherein x represents the in-hand pose, c_t the pose of the hand, and y_t indicates whether the robot has interacted with the environment reference element.

Optionally, in the entity (200) of the second aspect of the invention, the posterior probability of the in-hand pose is determined using a particle filter method.

Optionally, in the entity (200) of the second aspect of the invention, the posterior probability of the in-hand pose is determined on the basis of:

$$\frac{1}{N}\sum_{i=1}^{N} p\left(y_T \middle| x_{T-1}^{(i)}, c_T\right)$$

Optionally, in the entity (200) of the second aspect of the invention, the particles of the particle filter method are updated based on an interaction status information for a given particle.

Optionally, in the entity (200) of the second aspect of the invention, the processor is further configured to estimate, at a further earlier time instant preceding in time the earlier time instant, the in-hand pose on the basis of information that is different from information referring to interaction with the environment.

Optionally, in the entity (200) of the second aspect of the invention, the processor is configured to estimate at the further earlier time instant by estimating the in-hand pose on the basis of predetermined hand position information given in advance, and/or sensor information indicating an interaction between the hand and the object.

Optionally, in the entity (200) of the second aspect of the invention, the processor is configured to estimate the in-hand pose by estimating the in-hand pose on the basis of a model of the object, wherein the model of the object is preferably a geometrical model.

Optionally, in the entity (200) of the second aspect of the invention, the interaction status information is determined on the basis of sensor modality information.

Optionally, in the entity (200) of the second aspect of the invention, the interaction status information is based on the output of one or more amongst a force-torque sensor, a tactile sensor, an image sensor, a 3D sensor.

Optionally, the entity (200) of the second aspect of the invention is comprised by a robot.

In another aspect, it is provided a computer program comprising instructions configured to perform, when said instructions are executed on a computer, any of the steps described in the above first embodiment and/or its optional aspects.

In another aspect, it is provided a medium comprising instructions configured to execute, when said instructions are executed on a computer, any of the steps described in the above first embodiment and/or its optional aspects.

BRIEF DESCRIPTION OF FIGURES

Figure 1 is a flow chart illustrating a method according to an embodiment of the present invention;

Figure 2 is a flow chart illustrating a method according to a further embodiment of the present invention;

Figure 3 shows a block diagram of a device according to one embodiment of the present invention;

Figure 4 is a schematic representation of a robot placed in an environment and holding an object, according to one example of the invention;

Figure 5 shows a block diagram of a computer suitable for executing instructions according to one embodiment of the present invention.

DETAILED DESCRIPTION

The invention is based, amongst others, on the inventors' recognition that an in-hand pose can be better estimated by considering possible interaction(s) between the robot, in particular the grasped object and/or the grasping hand, and the environment in which the robot is placed (or is in operation) or capable of moving.

With reference to the flow chart depicted in Figure 1, a description is now made of a first embodiment directed to a method for determining an in-hand pose of an object held by a robot. The in-hand pose indicates a position of an object held by the hand of a robot relatively to the hand (or more in general relatively to the robot), and may be expressed for instance by way of a 6-dimensional vector (this being a non-limiting example, see also further below) comprising translation and rotation values, which may include values relative to the hand or robot, or values relative to a reference system being outside/independent of the hand/robot; thus, the in-hand pose provides an indication of how the object is placed relatively to the hand or robot. For example, the in-hand position indicates a relative position (or relative placement) between a reference point of the object and a reference point of the robot (or of the robot's hand, or of another robot's part, as long as it is a reference point); preferably, the reference point indicates also an orientation of the object. Further explanations and examples are provided also further below. By robot it is intended any device capable of carrying out a series of actions, including movements (of the robot and/or of its extensions) and/or grasping object(s). A robot thus includes an industrial robot, a service robot, an interactive robot, a manipulator, etc. By hand it is herein referred to a component of the robot capable of grasping and/or holding an object, preferably while the hand and/or robot is moving. The hand thus includes any device capable of grasping and/or holding an object, and thus includes fingers, an end-effector (in the sense of an extension of the robot capable of grasping and/or holding), etc. In particular, the term hand is not restricted to a particular shape or construction, like for instance an anthropomorphic shape/construction.

At step S10, the hand of the robot is moved while holding an object in an environment. For example, once the object is grasped, the hand of the robot is moved along a trajectory; the movement or trajectory can be determined in a way that is for example random, according to predetermined rule(s), according to a predetermined pattern(s), programmed, under control of an operation, or any combination of these. By environment it is intended the surroundings of the robot, like for instance: a table or surface (or part(s) thereof), on which the robot is installed and can operate; a room (or part(s) thereof), a factory (or part(s) thereof) in which the robot can operate, etc., as well as any combination of these.

At step S20, it is estimated, at a given time instant, the in-hand pose with which the robot is holding the object. The estimation may be based on earlier interaction information, wherein the term earlier indicates that the interaction information refers to a point in time which precedes (in time) the given time instant at which the estimation is performed. The earlier in time also indicates that the interaction information represents data or evidence that has been obtained and it thus available at the time instant at which the estimation is made. The given time instant is a point in time at which the estimation is performed, preferably when taking into account tolerances implied in the determination of a point in time (i.e. the term is not restricted to an exact point in time, and may include a time interval for performing such estimation; similarly, the measurement or data are obtained at a time instant that may include a time interval as necessary for making measurements or acquisition).

The above introduced earlier interaction information include position information and interaction status information.

The position information indicates a hand position at an earlier time instant, wherein the earlier time instant is a time instant preceding in time the given time instant (at which the estimation is performed); in one example later illustrated, the given time instant is represented by T_i and the earlier time instant by T_{i-1}. The position information therefore represents the position of the robot’s hand at a point in time preceding the timing at which the estimation is performed, and may be obtained for instance by any suitable sensor as also below illustrated.

Turning to the interaction status information, this indicates whether the robot has interacted with the environment, preferably with an environment reference element, at the earlier time instant. The robot and the environment reference element are characterized by a relative (spatial) separation, which is preferably known or that can be calculated on the basis of reference point(s). This separation may be expressed in terms of (also relative) positions of the two elements, relative distance, relative angle, etc. or any combination of these. The environment reference element represents one element included in the environment, and which is preferably predetermined (hence, the term reference, which can be interchanged with predetermined); reference or predetermined element implies that the separation (in space) between the element and the robot (or parts thereof) is known, or can be calculated on the basis of predetermined point(s) of the robot and the environment. The element (and correspondingly the relative position/distance/angle between the element and the robot) can be dynamically changed, as long as the spatial separation between the robot and that element is known (or can be calculated). For example, the robot may be placed on a table, with the surface (or a portion thereof) of the table representing an environment reference element; the relative height of one predetermined point of the robot from the table's surface is an example of a predetermined or reference separation between the reference element and the robot. In other examples, the element may be represented by a wall, by a line or segment in the environment, by a specific point in the environment, or any combination thereof. In a further example, the robot itself or a known portion or surface of the robot may be regarded as the reference element, and the relative separation may be the separation between the refence part of the robot (e.g. a part of the robot's basement, or a joint, etc.) and another reference point of the robot.

As said, the interaction status information indicates whether there has been any robot-environment interaction.

Such robot-environment interaction can be either (i) a direct interaction, when for instance the robot (of one of its components including the hand) interacts with the environment or (ii) an indirect interaction, when for instance the object held by the hand interacts with the environment, or any of their combination. In fact, while the object is grasped or held by the robot (i.e. by the robot's hand), the object can be considered as a part of the robot for the purpose of determining the interaction. In one example of indirect touch, one may consider the case wherein the object is a pen being held while pointing downwards, and the robot is placed on a table (an example of the environment); if the hand is moved towards the table, it is likely that the object interacts with the table (e.g. by touching the table) before the robot's hand interacts with the table; in this case, it can be determined that the object – and consequently the robot in an indirect manner – has interacted with the table. In another example, wherein the pen is held pointing upwards, the hand of the robot (or another component of the robot like e.g. an arm) may touch the table instead of the object, thus resulting in a (direct) interaction with the table. In these examples, the interaction is represented by a touch state. However, the invention is not limited to a touch state, as in fact a touch as herein used also includes the case wherein the robot/hand and/or object graze the environment, in the sense that the robot/hand and/or object is about to touch the environment but just misses touching the environment. In other words, a touch includes also the case where the robot goes very close to touching the environment, e.g. close to touching the environment within a given threshold. In general, therefore, the interaction includes any action that physically couples the robot with the environment as a consequence of the movement of the grasped object. Suitable sensors can be used as also later illustrated.

The method of Figure 1 can also be explained in other illustrative words: at time T_{i-1}, it is determined whether or not the robot interacts, e.g. touches in the above sense, the environment; at the same time instant T_{i-1}, the hand’s position is also measured. Then, at time T_i, the in-hand pose is estimated based on (i) the measurement at time T_{i-1} of the hand position and (ii) the information as to whether at that time instant T_{i-1} there was a robot-environment interaction. In further other words, at an earlier time instant data is collected (“evidence”, since it is based on measurable facts) as to the hand position and whether the robot interacted or not with the environment; such collected data is used at the later time T_i to estimate the in-hand pose. As found by the inventor, this allows an estimation of the hand-in pose by using some information that can be easily obtained, i.e. by performing only simple measurements and/or using simple sensors, and by means of relatively easy computations.

Optionally, in the method of the present embodiment, the position information indicates a plurality of hand positions at respective earlier time instants, and the status interaction information indicates whether the robot, in correspondence of the respective earlier time instants, has interacted with the environment reference element. In other words, it is possible to collect hand position(s) also at one further or more time instants T_{i-2}, T_{i-3}, T_{i-4}, … and respective robot-environment interaction status(es) at those time instants T_{i-2}, T_{i-3}, T_{i-4}, …; the in-hand pose can thus be estimated on the basis of all (or some of) such available past information.

Optionally, in the method of the present embodiment, the earlier interaction information includes interaction status information indicating that the robot has interacted with the environment reference element at least at one earlier time instant, which may be indicated as the interaction time instant. At this interaction time instant, the position information thus indicates the position of the hand when the robot-environment interaction occurred. It follows that the in-hand pose, in this optional scenario, is estimated on the basis of information obtained at an earlier time instant at which a robot-environment interaction occurred. In fact, it has been found that if there has been (at least) one robot-environment interaction at a past time instant T_{i-1}, then the accuracy of the estimated in-hand pose at time T_i can be largely improved. Thus, a high accuracy can be arrived at, while using a limited number of simple measurements, as well as a relatively low number of computations.

Optionally, in the method of the present embodiment, the earlier interaction information includes interaction status information indicating that the robot has interacted with the environment reference element at least at two, preferably at least at three, earlier time instants; the position information indicates the hand positions at the respective at least two, and preferably respectively three, interaction time instants. The in-hand pose can thus be estimated on the basis of information obtained in correspondence of at least two, preferably three, time instants at which the robot-environment interaction occurred. In other words, the in-hand pose can be estimated after a robot-environment interaction has occurred at least two, or correspondingly at least the three times, before the instant at which the estimation is computed. In further other words, the in-hand pose estimate can be refined after each interaction. In fact, it has been found that when there have been at least two, preferably three, earlier robot-environment interactions, it is possible to further increase the accuracy of the in-hand pose estimation. In particular, these cases show an improved accuracy that is over proportional relatively to the increased processing resources, and when compared for instance to the case where more earlier robot-environment interactions occurred (i.e. the marginal increase of accuracy is not commensurate to the additional computational power requires when a much larger number of interaction time instants is considered). At any rate, at least one interaction leads to a large increase in the estimated in-hand pose, with plural interactions increasing such accuracy.

Optionally, in the method of the present embodiment, estimating the in-hand pose comprises determining a posterior probability of the in-hand pose based on the earlier interaction information. Examples will be provided also below, e.g. with reference to Baysian models.

Optionally, in the method of the present embodiment, estimating the in-hand pose comprises calculating the in-hand pose based on

$$p\left(x \middle| \{y_t, c_t\}_{t=1}^{T}\right)$$

- Formula (a) -

wherein x represents (the variable indicating) the in-hand pose, c_t the (variable indicating) pose of the hand, and y_t (the variable that) indicates whether the robot has interacted with the environment reference element. Examples and further illustrations will be given below.

Optionally, in the method of the present embodiment, the posterior probability of the in-hand pose is determined using a particle filter method. Also here, examples and further illustrations will be given further below.

Optionally, in the method of the present embodiment, the posterior probability of the in-hand pose is determined on the basis of:

$$\frac{1}{N}\sum_{i=1}^{N} p\left(y_T \middle| x_{T-1}^{(i)}, c_T\right)$$

- Formula (b).

Optionally, in the method of the present embodiment, the particles of the filter method are updated based on an interaction status information for a given particle. In other words, when updating the particles, it matters whether the particle refers to an interaction having occurred or not, e.g. whether the particle refers to a touch having occurred or not. In particular, the particles are updated on the basis of those particles for which an interaction (e.g. a touch) has occurred. In fact, it has been found that by updating the particles on the basis of those particles corresponding to a touch state, it is possible to increase the accuracy of the estimation of the in-hand pose. In particle filtering methods, the updating of the particles is also called sometimes re-sampling. A general explanation of particle filters, to which the present finding can be applied, can be found e.g. in "Del Moral, Pierre, 1996, Non Linear Filtering: Interacting Particle Solution," or at http://www.it.uu.se/katalog/andsv164/Teaching/Material/PF_Intro_2014_AndreasSvensson.pdf ("An introduction to particle filters", presentation by Andreas Svensson, Department of Information Technology Uppsala University; June 10, 2014).

Optionally, in the method of the present embodiment, it is estimated, at a further earlier time instant preceding in time the earlier time instant, the in-hand pose on the basis of information that is different from information depending on interaction with the environment. In particular, the further earlier time instant includes an initial time instant (e.g. when the method for estimating is started or about to be started) at which there are no measurements available such that predetermined information are used to initialize the method, i.e. predetermined information (that are not necessarily measurements but may be previous measurement and/or information obtained by other method(s)) are used to start the estimation process at the next time instant T_i.

Optionally, in the method of the present embodiment, it is estimated at the further earlier time instant the in-hand pose on the basis of predetermined hand position information given in advance (e.g. known), and/or sensor information indicating an interaction between the hand and the object.

Different sensors are suitable for providing an indication of interaction between the hand and the object, as also further later illustrated.

Optionally, in the method of the present embodiment, estimating the in-hand pose includes estimating the in-hand pose on the basis of a model (preferably, a geometrical model) of the object. Having in fact knowledge of the model, it is possible to determine more accurately the placement in space of the object while being held by the hand – it is then possible to perform tasks like for example the peg-in-hole task more accurately (noting that performing the task is optional, what matters being the in-hand pose estimation). A CAD model is an example of a model for the object. It is noted that a model of the object is not necessarily required to obtain the in-hand pose, as in fact the object (or a class of objects) can be often approximated or represented with one single information, preferably known in advance or which can be assumed, estimated, or measured (or a combination thereof). For instance, in the case of a spherical object (e.g. a ball), the in-hand pose can be defined relatively to the sphere's centre; in the case of an elongated object (i.e. an object which predominantly extends over one dimension, like the length, making the other directions negligible, e.g. a pen, a stick), the in-hand pose can be defined relatively to one of the distal ends of the elongated object, or relatively to the centre or another point of the elongated object, etc. As it can be seen from these examples, it is not strictly necessary to represent the in-hand pose with a 6 dimensional vector, as for instance it may be enough to specify a distance between a reference point of the object and the reference point of the hand, or an angle between a reference dimension (e.g. longitudinal extension) of the object and a reference axis of the hand/robot. As said, the information relating to the model (or its approximation) does not need to be predetermined; for instance, image recognition could be performed on an object (as grasped, or (about) to be grasped by the hand), so that the object can be classified, recognized or estimated, such that the in-hand pose can be determined based on the classification/recognition/estimation of the object. Also, above reference has been made to an analytical geometrical shape as a model, and in general to any model that, e.g. by taking the geometry into account, allows estimating the object's position in space. If (different) sensing modalities are used, a model representing those modalities may be used, like for instance a model representing electric or thermal conductivity. If the object is flexible, the model may include its stiffness, elasticity, viscosity, etc. or any combination, optionally in addition to a model describing geometry and/or other sensing modalities.

More examples: You have already mentioned analytical geometrical shapes rather than CAD models. I think any model needs to be connected to geometry because we are estimating the object's position in space. If different sensing modalities are used, a model representing those modalities may be used (e.g. electric or thermal conductivity). If the object is flexible, the model may need to include its stiffness/elasticity/viscosity beyond simple geometry.

Optionally, in the method of the present embodiment, the interaction status information is determined on the basis of sensor modality information. The sensor modality information represents information provided by a sensor suitable for sensing sensor modality, i.e. a sensor suitable to detect one aspect of a stimulus or what is sensed/detectable after a stimulus. Other example are such sensors are presented by a proximity sensor, an infrared light sensor, an electric contact sensor, etc. or a combination thereof.

Optionally, in the method of the present embodiment, the interaction status information is based on the output of one or more amongst a force-torque sensor, a tactile sensor (including are sensors), an image sensor, a 3-D sensor, etc.

or a combination thereof. For instance, a force-torque sensor output can be used to determine whether the object and/or robot has touched the environment. Image recognition (on an image taken while the object is moved in the environment) may be used to determine if the object touches the environment; also, image recognition may be used to determined where the object is located of where its bounds are (so as to determine whether this results in an interaction with the environment), etc. (these methods may be combined). Similar considerations apply to other sensors.

With reference to figure 2, a second embodiment is described directed to a method for determining an in-hand pose of an object held by the robot. Unless otherwise stated, the same considerations as above apply, such that they will not be repeated. An initialisation is performed at step S110, which includes providing an initial estimation at time T_0 for the in-hand pose without relying on any measurement data; the initial estimation can be provided for example on the basis of a predetermined hand position given in advance, a predetermined (e.g. a priori) probability distribution for the in-hand pose like for instance a flat probability distribution, sensor information indicating an interaction between the hand and the object (as for instance given by a tactile sensor, an array sensor, etc.). At step s110, the robot is controlled such that the hand holding the object is moved along a trajectory as also above explained. The initial estimation and the start of movement may be done at the same time or at different time instants.

At time instant T_1 exemplified in step S150, and in particular after the hand holding the object has performed at least some movement (i.e. the hand has moved at least by a certain amount), it is determined whether a robot-environment interaction occurs and respective interaction status information at time T1 is generated; for instance, “1” indicates that an interaction occurred, while “0” indicates that an interaction has not occurred (other representations are possible). Further, the position of the hand is also measured so that position information at time T_1 is obtained. In this way, it is possible obtaining earlier interaction information at time T_1, which includes information on the hand position and on the robot-environment interaction at time T_1. Thus, the robot-environment interaction and hand position are measured and refer to the same time instant T_1 (which, as said, especially when taking tolerances into account may be regarded as a measurement and/or detection period); the earlier time information are preferably prepared at the same time, but not necessarily as in fact they may be generated (shortly) after obtaining the measurements.

At time T_2 exemplified in correspondence of step S160, an estimation of the in-hand pose is performed, by using the earlier interaction information obtained at time T_1. Thanks to the contribution of the measurement data, the in-hand pose can be estimated with a certain accuracy. In case the interaction status information indicates that a robot-environment interaction occurred once, e.g. that the robot touched (or almost touched) the environment reference element, the in-hand pose can be estimated even far more accurately.

It is possible to iterate the process, e.g. by collecting position information and interaction status information at time T_2 (or at a subsequent time instant, i.e. after the estimation at T_2), i.e. by repeating step S150 at time instant T_2 so as to obtain earlier interaction status information at time instant T_2; such earlier interaction status information may include also the measurement at time instant T_1, i.e. both of the data available at T_1 and T_2 may be included therein, or only the most recent data of time instant T_2. The method can then proceed to step S160 wherein an estimation is performed at time instant T_3 by taking into account the newly available earlier interaction status information. The process can be further iterated at subsequent time instants T_3 , T_4 , … In this way, it is possible to further improve the accuracy of the in-hand pose estimation. In particular, when the robot has interacted with the environment at least two or preferably three times, it is possible to further improve the accuracy as also above explained. We note that the initialisation step S110 as well as the iteration are indicated with dashed lines in figure 2 to highlight their optionality, as in fact the invention also works as long as data are collected at a time T_{i-1} and the estimation is performed at a subsequent time T_i based on the data collected at T_{i-1}.

The above method(s) can be executed by a computer, by processor, by a combination of processor(s) and/or processing unit(s), by a single device, by a plurality of interconnected devices (e.g. in a cloud), or a combination thereof.

Further embodiments and example are explained in the following, when noting that what has been explained above equally applies to the below further embodiments and examples unless otherwise stated, as well as vice versa, so that repetitions are avoided.

With reference to figure 3, a third embodiment is now described directed to an entity 200 for determining an in-hand pose of an object held by a robot. The entity can be realised by any combination of software and/or hardware, and can be concentrated into one single device or distributed across multiple devices preferably interconnected (over any suitable communication network(s)) with each other. The entity 200 comprises a movement controller 210 and a processor 220.

The hand movement controller 210 controls the hand of the robot so that it is moved in an environment where the robot is placed or is in operation, while the hand is holding the object. Thus, the movement controller causes the movement of the robot’s hand. The movement may be according to a continuous trajectory or a set of different trajectories each representing a section (or stretch) of movement.

The processor 220 is configured to estimate, at a given time instant T_i, an in-hand pose with which the robot is holding the object based on earlier interaction information referring to an earlier time instant T_{i-1}. The earlier interaction information includes position information and interaction status information. The position information indicates a position of the hand at time instant T_{i-1}. The interaction status information indicates whether the robot has interacted with the environment reference element at instant T_{i-1}.

Therefore, based on the data referring to hand position and robot-environment interaction at time instant Ti-1, it is possible to estimate at time instant Ti the in-hand pose of the object.

The entity of the present embodiment is further configured to perform any of (and any combination of) the operations described above or in the following, such that repetitions are omitted.

The entity 200 may be included within the robot, or placed remotely from the robot while being in communication with the same. In another example, the entity 200 may be distributed, for example partly placed within the robot and partly placed remotely, or realized in a distributed manner all remotely from the robot.

Figure 4 shows an illustrative example of a robot configuration to which the present invention may be applied. As it can be seen, in this example robot R includes a hand M, including two fingers R1 and R2 suitable for grasping and holding an object O. In this example, the object has an elongated shape, such that it can be approximated to a stick having length L, while neglecting the other dimensions. Other objects and shapes are possible. Robot R is placed (or is in operation) in an environment. More in particular, in the example, robot R is mounted on a table T (T may in general represent a surface, e.g. of the table, pavement, etc.). The environment may of course include other elements, like for instance walls, pieces of furniture, industrial tools, etc., which are not represented for simplicity. The table T represents a reference element of the environment, in the sense that it is known a relative separation between the robot and the environment reference element T. In this example, a relative separation between the robot R and the reference environment element T can be represented by a height H of the robot R from the table T. More in particular, the height H may be known with reference to a point P1 of the robot R (when the robot R finds itself in a certain position or configuration) and a point P2 of the table T; the geometry and the kinematics will then allow determining the height H' in any other position or configuration that the robot and its components may assume while in operation, i.e. while the robot is moving. Once the object O is grasped, the robot is controlled to move the object in the environment. While moving, the robot-environment interaction as well as the corresponding hand position are detected or measured at time instant T_{i-1}; the collected measurements or data are then used at time instant Ti to estimate the in-hand pose. When the robot interacts with (e.g. touches) the environment, and in particular the environment reference element, the estimation of the in-hand pose can be highly increased. This may be explained as follows: When the robot R touches the table T, the relative separation between the table and the robot, which is known or that can be calculated (see above, based e.g. on movement/kinematic), represents an additional piece of available information that can be used to improve the in-hand pose estimation.

The in-hand pose estimation will then indicate a relative placement of the object relatively to the robot, in the sense of being relative to any part of the robot. In one example, the in-hand pose may be relative to the hand of the robot, and may for instance be indicated by a 6-dimensional vector providing translation and rotation of the object O relatively to the hand; in another example, the in-hand pose for the object O illustrated in figure 4 may be given by an information indicating whether the object O points upwards or the downwards relatively to the hand, i.e. it does not need be necessarily represented by a 6 dimensional vector.

With reference to figure 5, a further embodiment will be described directed to a computer program comprising instructions configured to execute, when the instructions are executed on a computer, any or a combination of the steps of the method and the variants thereof as described above, e.g. with reference to the first embodiment. Figure 5 illustrates a block diagram exemplifying a computer (500) capable of running the aforesaid program. In particular, the computer (500) comprises a memory (530) for storing the program instructions and/or the data necessary for its execution, a processor (520) for carrying out the instructions themselves and an input/output interface (510). The instructions may be those or executing any of the steps, or any combination of the steps, herein illustrated.

In another non-illustrated embodiment, it is provided a medium for supporting a computer program configured to perform, when the program is run on a computer, one or a combination of the steps according to the method described above, e.g. with reference to the first embodiment. Examples of a medium are a static and/or dynamic memory, a fixed disk or any other medium such as a CD, DVD or Blue Ray. The medium also comprises a means capable of supporting a signal representing the instructions, including a means of cable transmission (ethernet, optical, etc.) or wireless transmission (cellular, satellite, digital terrestrial, etc.).

In another non-illustrated embodiment, it is provided a system including a robot and an entity as illustrated for instance with reference to the embodiment depicted in Figure 3. In realizing the system, the entity may be placed remotely from the robot, or partially within or in proximity of the robot and partially outside the robot. In other examples, the entity is integrated with or within the robot to form a system for estimating the in-hand pose, or is placed in proximity of (e.g. attached to) the robot.

In the following, an illustrative example is provided showing how the in-hand pose can be estimated. More in particular, in this example, an in-hand pose estimation method is formulated by a particle filter framework to update estimate gradually by exploiting interactions between the grasped object and the environment.

Many industrial robots are generally very precise in position, and it can be assumed that the estimation error of the grasped pose is less than 5 [mm]. In the framework of this example, the robot makes a (at least one) contact between the grasped object and object(s) in the environment (above also called element(s) of the environment) such as a table to update the estimate from robot encoder information when it collides to the environment while knowing the table position in robot coordinates. The robot encoder information represents an example of the hand position information. By repeating these interactions, the objective is to achieve less than 1 [mm] accuracy of in-hand pose estimation. Here we also assume that the grasped object is fixed well in the robotic hand, and the pose cannot be changed.

Let the relative grasped object pose, hand pose at t-th interaction (contact), and status at the time, be x, c_t, and y_t, respectively. Here, x and c_t are 6-dimensional vectors including translation (at Euclidean space coordinate $\in R^3$) and rotation (at Euler angle R^3), and y_t is a binary value ($\in \{0,1\}$) indicating contact or non-contact.

The estimate, in this example, can be updated using the particle filter, e.g. as follows. The objective is to estimate the relative pose x of the grasped object for a set of measurements obtained by the interaction with environment $\{y_t, c_t\}^T_{t=1}$, which is equivalent to, in Bayesian setting, obtaining a posterior probability p (x| $\{y_t, c_t\}^T_{t=1}$) . The posterior probability can be given by

$$p\left(x \middle| \{y_t, c_t\}_{t=1}^{T}\right) \propto p(x) \prod_{t=1}^{T} p(y_t|x, c_t) \quad (1)$$

$$\propto p\left(x \middle| \{y_t, c_t\}_{t=1}^{T-1}\right) p(y_T|x, c_T) \quad (2)$$

The above indicates that the posterior probability of the relative pose after the *T*-th interaction can be calculated by that after the T - 1-th interaction

$$p\left(x \middle| \{y_t, c_t\}_{t=1}^{T-1}\right)$$

and the likelihood at *T*-the interaction with environment.

However, in many cases, the posterior probability

$$p\left(x \middle| \{y_t, c_t\}_{t=1}^{T-1}\right)$$

cannot be computed in closed form, because the marginalization

$$\int p\left(x \middle| \{y_t, c_t\}_{t=1}^{T-1}\right) p(y_T|x, c_T)\ \mathrm{d}x$$

in the right-hand side of formula (2) cannot be computed in analytical way. In the case that the posterior probability cannot be given in the closed form, several approximation methods have been proposed in Bayesian statistics and the machine learning field; amongst them, for the present example, the particle filtering method is used, one of the sampling-based approximations. The family of sampling-based methods gives guarantee of asymptotic convergence to the real posterior by increasing the number of particles, compared to variational methods or Kalman filtering. At this time, the objective is to achieve a highly precise estimation of the relative pose; accordingly, a sampling-based method has been chosen to obtain higher accuracy, rather than optimization-based methods which are advantageous in fast computation.

In particle filter, marginalization in the right hand side of the formula (2) can be approximated, using particles of pose estimates

$$\left\{x_{T-1}^{(i)}\right\}_{i=1}^{N}$$

sampled from the posterior probability

$$p\left(x\middle|\left\{y_t, c_t\right\}_{t=1}^{T-1}\right)$$

at T-1 times, as follows:

$$\int p\left(x\middle|\left\{y_t, c_t\right\}_{t=1}^{T-1}\right) p\left(y_T \middle| x, c_T\right) \mathrm{d}x \simeq \frac{1}{N}\sum_{i=1}^{N} p\left(y_T \middle| x_{T-1}^{(i)}, c_T\right),$$
$$\text{with } \left\{x_{T-1}^{(i)}\right\}_{i=1}^{N} \sim p\left(x\middle|\left\{y_t, c_t\right\}_{t=1}^{T-1}\right). \qquad (3)$$

Here the likelihood $p\left(y_T \middle| x_{T-1}^{(i)}, c_T\right)$ for each particle $x_{T-1}^{(i)}$ can be given by computing geometrically the distance $d_T^{(i)}$ between the table and the robot hand position c_T in robot coordinates and defined as follows:

$$p\left(y_T \middle| x_{T-1}^{(i)}, c_T\right) = \begin{cases} 1 & \left(d_T^{(i)} \leq threshold\right) \\ 0 & \left(d_T^{(i)} > threshold\right) \end{cases}, \qquad (4)$$

Where *threshold* is a small enough value, say about 0.5[*mm*].

This enables approximated posterior computations using particles; the next sampling of particles is done based on the posterior probability after updating $p\left(x\middle|\left\{y_t, c_t\right\}_{t=1}^{T-1}\right)$. Here for each particle in formula (3), the likelihood for updated posterior probability can be computed as below, and the new particle is sampled in proportional probability based on the likelihood:

$$w_T^{(i)} = p\left(x_{T-1}^{(i)} \mid \{y_t, c_t\}_{t=1}^{T}\right) \simeq \frac{p\left(y_T | x_{T-1}^{(i)}, c_T\right)}{\sum_{i'=1}^{N} p\left(y_T | x_{T-1}^{(i')}, c_T\right)}. \quad (5)$$

In practice, using $\left\{w_T^{(i)}\right\}_{i=1}^{N}$ in formula (5) and N number of random variable $\left\{u_T^{(i)}\right\}_{i=1}^{N}$ sampled from uniform distribution in the range of [0,1), new particles $\left\{x_T^{(i)}\right\}_{i=1}^{N}$ can be obtained as follows:

$$x_T^{(i)} = x_{T-1}^{(j)} \quad s.t. \quad \sum_{k=1}^{j-1} w_T^{(k)} \leq u_T^{(i)} \leq \sum_{k=1}^{j} w_T^{(k)}. \quad (6)$$

$$\left\{x_T^{(i)}\right\}_{i=1}^{N}$$

By repeating this procedure, every time a robot-environment interaction occurs, i.e. there is an interaction between grasped object and environment, it is possible to update the posterior probability of the relative in-hand pose to obtain a more accurate estimate.

In the above, reference has been made to a prediction method. However, while recalling that one invention’s recognition lies in that the in-hand pose estimate can be refined (improved) after each interaction, it is noted that the invention and such recognition(s) can be achieved also by a filtering method. For instance, in a filtering method, an update is performed for each particle; at this point, the new observation (measurement) is used; using the weight(s), the current distribution is obtained.

In the present description, reference has been made to parts or units like sensor(s), memory, processor, etc. The invention is not limited to the specific elements and/or units therein described, and in fact it equally applies to respective means; thus, the controller, memory, processor, sensor etc. may be substituted by respective controlling means, memory means, processing means, sensing means, etc., respectively. These units (or respective means) can be implemented as distinct/self-contained units/entities or as distributed units/entities (i.e. implemented through a number of components connected to one another, whether physically near or remote); these, be they concentrated or distributed, can further be implemented through hardware, software or a combination thereof.

Many of the embodiments and examples have been explained with reference to steps of methods or processes. However, what has been described can also be implemented in a program to be run on a computing entity (also concentrated or distributed) or an entity whose means are suitably configured. As illustrated above, the entity can be implemented in a single device, via HW (hardware)/SW (software) or a combination thereof, or in multiple interconnected units or devices (likewise HW, SW or a combination thereof). Naturally, the description set forth hereinabove concerning embodiments and examples that apply the principles recognised by the inventors is provided solely by way of example of these principles and therefore it should not be understood as a limitation of the scope of the invention claimed herein.

CLAIMS

1. Method for determining an in-hand pose of an object held by a robot, the method comprising the steps of:

- moving, in an environment, a hand of the robot holding an object;
- estimating, at a given time instant, an in-hand pose with which the robot is holding the object based on earlier interaction information, the earlier interaction information including

    position information indicating a hand position at an earlier time instant, and

    interaction status information indicating whether the robot has interacted with an environment reference element at the earlier time instant,

  the earlier time instant being a time instant preceding in time the given time instant.

2. The method of claim 1, wherein the position information indicates a plurality of hand positions at respective earlier time instants, and the status interaction information indicates whether the robot, in correspondence of said respective earlier time instants, has interacted with the environment reference element.

3. The method of claim 1 or 2, wherein the earlier interaction information includes interaction status information indicating that the robot has interacted with the environment reference element at least at one earlier time instant.

4. The method of any of claims 1 to 3, wherein the earlier interaction information comprises interaction status information indicating that the robot has interacted with the environment reference element at least at two, preferably at

least three, earlier time instants, and the position information indicates the hand position at the corresponding at least two, and respectively three, interaction time instants.

5. The method of any of claims 1 to 4, wherein estimating the in-hand pose comprises determining a posterior probability of the in-hand pose based on the earlier interaction information.

6. The method of claim 5, wherein estimating the in-hand pose comprises calculating the in-hand pose based on

$$p\left(x \middle| \{y_t, c_t\}_{t=1}^{T}\right),$$

wherein x represents the in-hand pose, c_t the pose of the hand, and y_t indicates whether the robot has interacted with the environment reference element.

7. The method of claim 5 or 6, wherein the posterior probability of the in-hand pose is determined using a particle filter method.

8. The method of claim 7, wherein the posterior probability of the in-hand pose is determined on the basis of:

$$\frac{1}{N}\sum_{i=1}^{N} p\left(y_T \middle| x_{T-1}^{(i)}, c_T\right)$$

9. The method of claim 7 or 8, wherein the particles of the particle filter method are updated based on an interaction status information for a given particle.

10. The method of any of the preceding claims, including:

estimating, at a further earlier time instant preceding in time the earlier time instant, the in-hand pose on the basis of information that is different from information depending on interaction with the environment.

11. The method of claim 10, wherein the estimating at the further earlier time instant includes estimating the in-hand pose on the basis of predetermined hand position information given in advance, and/or sensor information indicating an interaction between the hand and the object.

12. The method of any of claims 1 to 11, wherein estimating the in-hand pose includes estimating the in-hand pose on the basis of a model of the object, wherein the model of the object is preferably a geometrical model.

13. The method of any of claims 1 to 12, wherein the interaction status information is determined on the basis of sensor modality information.

14. The method of any of claims 1 to 13, wherein the interaction status information is based on the output of one or more amongst a force-torque sensor, a tactile sensor, an image sensor, a 3D sensor.

15. An entity (200) for determining an in-hand pose of an object held by a robot, the entity comprising:

- a movement controller (210) for causing the hand of the robot to move in an environment, while the hand is holding an object;
- a processor (220) configured to estimate, at a given time instant, an in-hand pose with which the robot is holding the object based on earlier interaction information, the earlier interaction information including

position information indicating a hand position at an earlier time instant, and

interaction status information indicating whether the robot has interacted with the environment reference element at the earlier time instant,

the earlier time instant being a time instant preceding in time the given time instant.

16. The entity (200) of claim 15, wherein the position information indicates a plurality of hand positions at respective earlier time instants, and the status interaction information indicates whether the robot, in correspondence of said respective earlier time instants, has interacted with the environment reference element.

17. The entity (200) of claim 15 or 16, wherein the earlier interaction information includes interaction status information indicating that the robot has interacted with the environment reference element at least at one earlier time instant.

18. The entity (200) of any of claims 15 to 17, wherein the earlier interaction information comprises interaction status information indicating that the robot has interacted with the environment reference element at least at two, preferably at least three, earlier time instants, and the position information indicates the hand position at the corresponding at least two, and respectively three, interaction time instants.

19. The entity (200) of any of claims 15 to 18, wherein the processor (220) is configured to estimate the in-hand pose by determining a posterior probability of the in-hand pose based on the earlier interaction information.

20. The entity (200) of claim 19, wherein the processor (220) is configured to estimate the in-hand pose by calculating the in-hand pose based on

$$p\left(x \middle| \{y_t, c_t\}_{t=1}^{T}\right);$$

wherein x represents the in-hand pose, c_t the pose of the hand, and y_t indicates whether the robot has interacted with the environment reference element.

21. The entity (200) of claim 19 or 20, wherein the posterior probability of the in-hand pose is determined using a particle filter method.

22. The entity (200) of claim 21, wherein the posterior probability of the in-hand pose is determined on the basis of:

$$\frac{1}{N}\sum_{i=1}^{N} p\left(y_T \middle| x_{T-1}^{(i)}, c_T\right)$$

23. The entity (200) of claim 21 or 22, wherein the particles of the particle filter method are updated based on an interaction status information for a given particle.

24. The entity (200) of any of claims 15 to 23, wherein the processor is further configured to estimate, at a further earlier time instant preceding in time the earlier time instant, the in-hand pose on the basis of information that is different from information referring to interaction with the environment.

25. The entity (200) of claim 24, wherein the processor is configured to estimate at the further earlier time instant by

estimating the in-hand pose on the basis of predetermined hand position information given in advance, and/or sensor information indicating an interaction between the hand and the object.

26. The entity (200) of any of claims 15 to 25, wherein the processor is configured to estimate the in-hand pose by estimating the in-hand pose on the basis of a model of the object, wherein the model of the object is preferably a geometrical model.

27. The entity (200) of any of claims 15 to 26, wherein the interaction status information is determined on the basis of sensor modality information.

28. The entity (200) of any of claims 15 to 27, wherein the interaction status information is based on the output of one or more amongst a force-torque sensor, a tactile sensor, an image sensor, a 3D sensor.

29. A robot comprising an entity according to any of claims 15 to 28.

30. A computer program comprising instructions configured to perform, when said instructions are executed on a computer, the steps of any of claims 1 to 14.

31. Medium comprising instructions configured to execute, when said instructions are executed on a computer, the steps of any of claims 1 to 14.

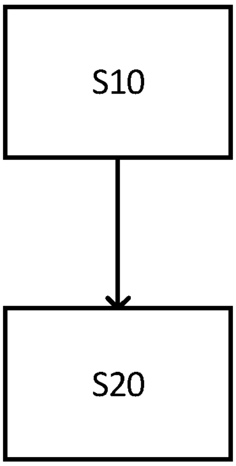


Fig. 1

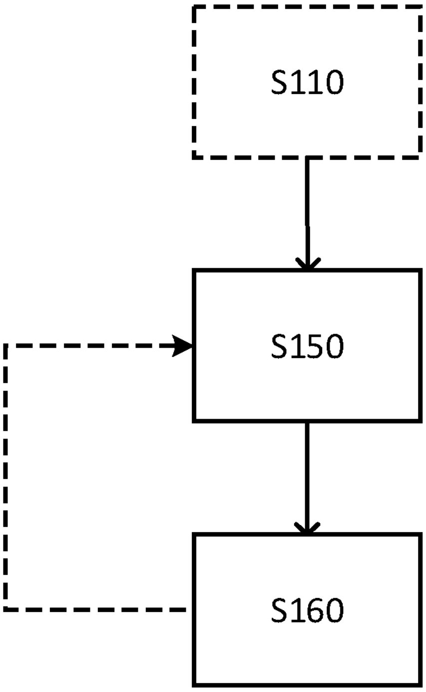


Fig. 2

Fig. 3

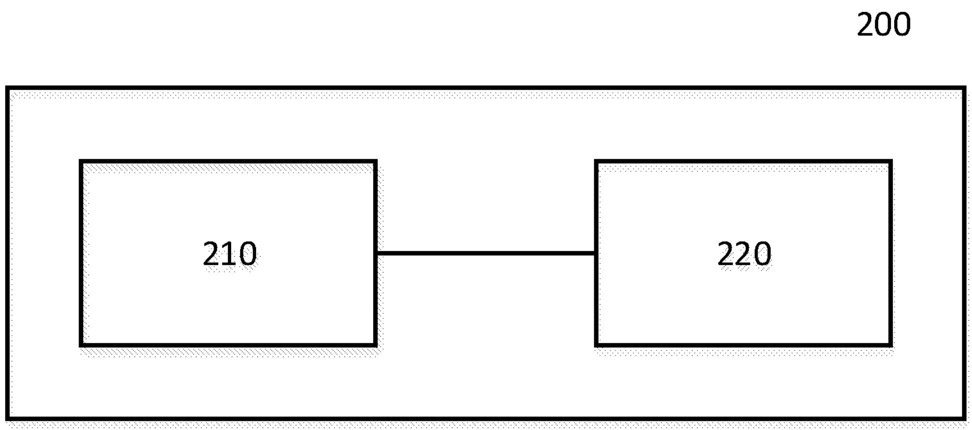


Fig. 4

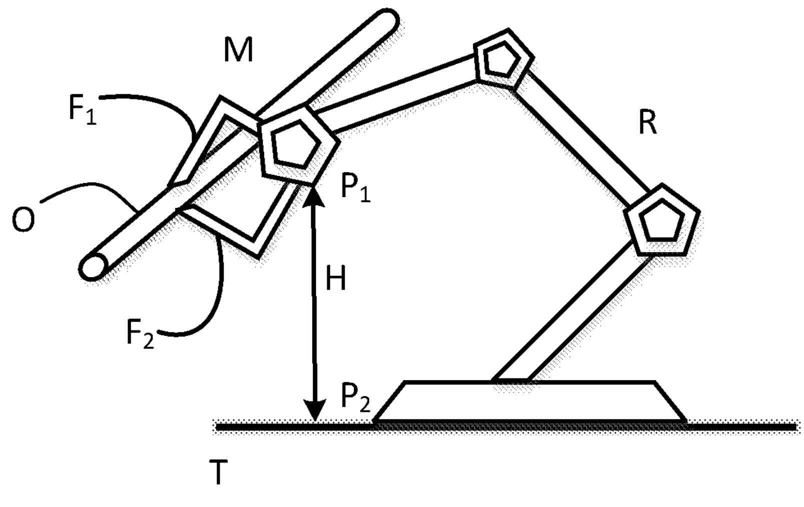
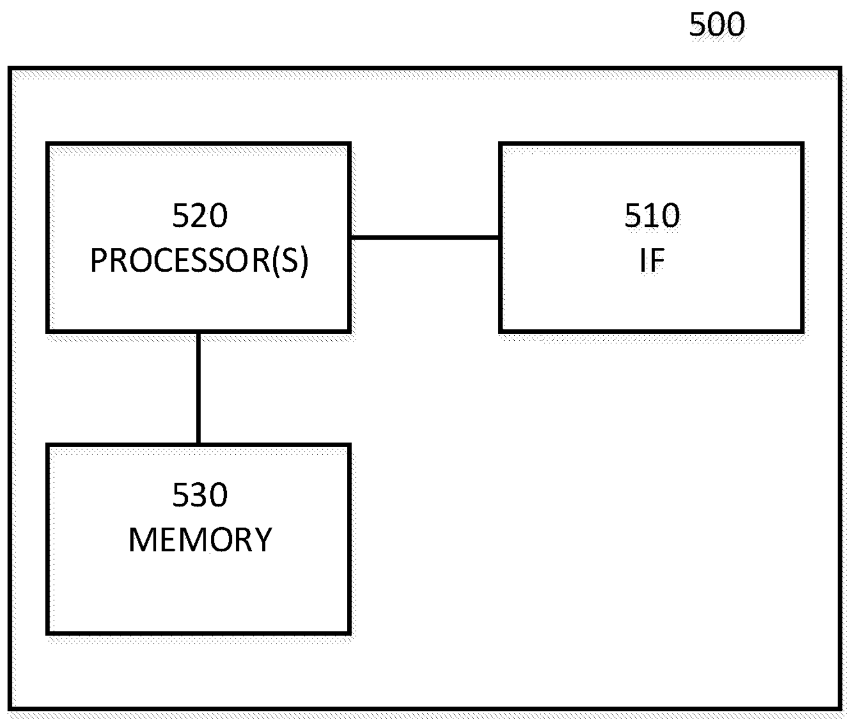


Fig. 5



INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2019/057734

A. CLASSIFICATION OF SUBJECT MATTER
INV. B25J9/16
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B25J G05B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	Kazuyuki Nagata ET AL: "Pose Estimation of Grasped Object from Contact Force or Joint Data of Manipulator", Transactions of the Society of Instrument and Control Engineers, 1 January 1992 (1992-01-01), pages 783-789, XP055706067, DOI: 10.9746/sicetr1965.28.783 Retrieved from the Internet: URL:https://pdfs.semanticscholar.org/28b9/913f4c1f0012b3f72362834027ec7985c8ed.pdf [retrieved on 2020-06-17]	1-4, 12-18, 26-31
Y	abstract	5-11, 19-25

	-/--	

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
18 June 2020	26/06/2020

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Orobitg Oriola, R

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	KARAYIANNIDIS YIANNIS ET AL: "Online contact point estimation for uncalibrated tool use", 2014 IEEE INTERNATIONAL CONFERENCE ON ROBOTICS AND AUTOMATION (ICRA), IEEE, 31 May 2014 (2014-05-31), pages 2488-2494, XP032650674, DOI: 10.1109/ICRA.2014.6907206 [retrieved on 2014-09-22]	1-4, 12-18, 26-31
Y	abstract Sections II to IV Section VI figure 1 -----	5-11, 19-25
Y	CHALON MAXIME ET AL: "Online in-hand object localization", 2013 IEEE/RSJ INTERNATIONAL CONFERENCE ON INTELLIGENT ROBOTS AND SYSTEMS, IEEE, 3 November 2013 (2013-11-03), pages 2977-2984, XP032537336, ISSN: 2153-0858, DOI: 10.1109/IROS.2013.6696778 [retrieved on 2013-12-26]	5-11, 19-25
A	the whole document -----	1-4, 12-18, 26-31
Y	DAVID ALVAREZ ET AL: "Tactile-Based In-Hand Object Pose Estimation Robot Formation based Grasping View project Phase Magnitude Diagram Control Systems Design View project Tactile-Based In-hand Object Pose Estimation", ROBOT 2017: THIRD IBERIAN ROBOTICS CONFERENCE, 1 November 2017 (2017-11-01), pages 703-718, XP055705164, DOI: 10.1007/978-3-319-70836-2_59 ISBN: 978-3-319-70835-5	5-11, 19-25
A	the whole document -----	1-4, 12-18, 26-31
Y	US 2011/246130 A1 (TAGUCHI YUICHI [US] ET AL) 6 October 2011 (2011-10-06)	5-9, 19-23
A	paragraph [0001] - paragraph [0013] paragraph [0020] - paragraph [0084] figure 1 -----	1-4, 14-18, 28-31

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/IB2019/057734

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2011246130 A1	06-10-2011	JP 5523378 B2	18-06-2014
		JP 2011221008 A	04-11-2011
		US 2011246130 A1	06-10-2011