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(54) Benævnelse: **STYRING OG REGULERING AF EN ROBOTS AKTUATORER UNDER HENSYNTAGEN TIL OMGIVELSESKONTAKTER**


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The invention relates to a method and to a device for the open-loop and closed-loop control actuators of a robot, taking mechanical contacts with a surrounding environment of the robot into consideration, wherein the robot comprises at least two parts, which are connected by way of an articulated joint drivable by an actuator, so that the parts can move relative to one another.

The detection and interpretation of mechanical environmental contacts is important for the open-loop and closed-loop control of parts of the robot movable by way of actuators (such as the links of a robotic arm), and in particular during robot-human interactions and collaboration. The key here is to distinguish between desirable contact events and undesirable contact events, which is to say collisions. Desirable contact events typically result from the task of the robot, such as handling an object and/or robot-human interactions in a predefined interaction range. Undesirable contact events are all contact events that are not desirable contact events. These are, in particular, collisions with objects or people in the surrounding environment of the robot, which are not located within the predefined interaction range, or also with the surrounding environment itself.

It is the object of the invention to provide an improved method and an improved device for the open-loop and closed-loop control of actuators of a robot, taking environmental contacts into consideration.

The invention is derived from the features of the independent claims. Advantageous refinements and embodiments are the subject matter of the dependent claims. Additional features, application options and advantages of the invention are derived from the following description, as well as the description of exemplary embodiments of the invention, which are illustrated in the drawings.

The aspect of the object in terms of the method is achieved by a method for the open-loop and closed-loop control of actuators of a robot, taking environmental contacts into consideration, wherein the robot comprises at least two parts, which are connected by way of an articulated joint drivable by an actuator. The parts may be links of a robotic arm, or the head, trunk or extremities of a humanoid. In particular, the robot can comprise multiple parts, which are connected by way of multiple articulated joints drivable by an actuator.

The method comprises the following steps. In a first step, a sensor system is used to ascertain and store a one-dimensional or multidimensional time-dependent variable G(t), which can be used to describe the action, as a function of the time, of one or more external contact forces $F_{ext}$ and/or of one or more external moments $M_{ext}$ on the parts. The variable G(t) may, in particular, be multidimensional, which is to say comprise multiple components g(t). $G(t) = [g_1(t), g_2(t), g_3(t), g_4(t)$, and so forth]. The variable G(t) may, for example, indicate one or more forces and/or one or more torques and/or one or more mechanical stresses and/or one or more pressures, or may indicate one or more one-dimensional or multidimensional variables ascertained therefrom. Components of the variable G(t) may relate to a jth articulated joint or a jth of the parts: $G_j(t)$, which is to say components of the variable G(t), are each ascertained for several of the parts and/or for several of the articulated joints.

The sensor system advantageously comprises measuring sensors for detecting forces, moments, stresses and/or pressures, furthermore an evaluation electronics unit and a memory unit for at least temporarily storing measurement results. The sensor system advantageously comprises proximity sensors, which is to say sensors that detect when an object approaches, without mechanical contact already existing. The sensor system advantageously comprises at least one sensor which is arranged on one of the parts and comprises sensor elements arranged in a planar manner for the position-sensitive detection of external forces $F_{ext}$ and/or moments $M_{ext}$ relative to the part, wherein the variable G(t) is ascertained based on the detected external forces $F_{ext}$ and/or moments $M_{ext}$. One example of this refinement is the use of an "artificial skin" comprising haptic sensors for detecting forces, moments, stresses, pressures, action sites and the like acting on the parts. The sensor system may, in particular, include a torque sensor and/or force sensor and/or acceleration sensor connected to one of the articulated joints for detecting a torque engaging on the articulated joint and/or a force engaging on the articulated joint and/or an acceleration engaging on the articulated joint.

Advantageously, the sensor system comprises a unit for estimating or predicting forces, moments, stresses and/or pressures based on current measurement data of the measuring sensors. Advantageously, historical measurement data of collisions with objects are used in the estimation/prediction.

In a second step, a condition B for this variable G(t) is provided. The condition B may be time-variant and/or dependent on the state of the robot. A simple condition B, for example, reads: the absolute value of G(t): |G(t)| is smaller than or equal to a limiting value F: $|G(t)| \leq F$. A possible I-dimensional formulation reads, for example: $|g_i(t)| \leq f_i$ where $G(t) = [g_i(t)]$; $F = [f_i]$ and $i = 1, 2, ..., I$. The condition B is advantageously selected in such a way that a distinction is possible between an action and a non-action of an external force $F_{ext}$ and/or moment $M_{ext}$ on the moving parts of the robot, wherein in the present case it is assumed that no action of an external force $F_{ext}$ and/or moment $M_{ext}$ exists as long as the condition B is satisfied.

The condition is advantageously selected so as to allow a distinction between an operation of the robot without the action of an external force or of an external moment and an operation of the robot with the action of an external force or an external moment.

The condition B may advantageously be ascertained, for example, in that the robot, with its parts movable by way of actuators, carries out random movements without the influence of external forces $F_{ext}$ (the gravitational force and possibly the Coriolis force shall be excluded), and parameters describing these movements (such as forces, moments, pulses and the like) are detected and evaluated by way of the sensor system. This range of parameters thus defines movements of the robot without the action of an external force $F_{ext}$.

In a third step, provided that the condition B is not satisfied by G(t) at a time $t_0$, a feature vector $\vec{M}$ is ascertained for the detected variable G(t) over a time interval $T = [t_a, t_e]$, where $t_a$ = start of the time interval, $t_e$ = end of the time interval, $t_0 \in T$ and $t_0 < t_e$, the feature vector comprising all the following components:

- a median or mean value of G(t) in the time interval T;
- a minimum and a maximum of G(t) in the time interval T;
- a deviation of G(t) from the median or from the mean value in the time interval T;
- a signal width of G(t) in the time interval T;
- a frequency spectrum of G(t) in the time interval T; and
- one or more characteristic frequencies of the frequency spectrum.

Following the above logic, $t_0$ indicates the point in time at which the predefined condition B is no longer satisfied by G(t), which is to say starting at which point in time at least one external force $F_{ext}$ or a moment acts on at least one of the parts or an articulated joint. Advantageously, the start $t_a$ of the time interval T and the end $t_e$ of the time interval T are time-dependent: $t_a = t_a(t)$ and $t_e = t_e(t)$, or only the end $t_e$ of the time interval T is time-dependent: $t_e = t_e(t)$. In the first case, for example, the interval T may chronologically shift with the time t. In the second case, the time interval T is greater to one side, which is to say the point in time $t_a$ is fixed and only $t_e(t)$ shifts with the time t. The time interval T advantageously has a duration of 10 ms, 20 ms, 50 ms, 75 ms, 100 ms, 250 ms, 500 ms, 750 ms, 1 s, 1.5 s, 2.0 s, 2.5 s, 3.0 s, 4.0 s, 5.0 s, 6.0 s, 7.0 s or 10 s.

In a fourth step, the ascertained feature vector $\vec{M}$ is classified based on predefined categories, which each indicate a contact type between at least one of the parts or one of the articulated joints and an object, which are each imparted by corresponding external contact forces $F_{ext}$ and/or external contact moments $M_{ext}$, to generate a classification result KE. In addition to a distinction between "desirable contact event" and "undesirable contact event," the categories advantageously also allow information to be provided about the type of the object triggering the contact, for example whether the contact site of the contact object is made of a hard or a less hard material. The categories can be easily ascertained by conducting appropriate test series and/or simulation calculations or from provided databases, for example from a data "cloud."

The classification of the feature vector $\vec{M}$ advantageously takes place by way of a support vector machine (SVM) and/or by way of a hidden Markov model and/or by way of a neural network and/or by way of a Gaussian process, or a combination thereof.

In a fifth step, the open-loop and/or closed-loop control of the at least one actuator for times $t > t_0$ take place as a function of the classification result KE. Depending on the ascertained classification result KE, open-loop and/or closed-loop control of the actuator advantageously takes place in such a way that a movement of the parts is stopped, slowed, accelerated, or a movement in the opposite direction is initiated. An accelerated movement and a movement in the opposite direction correspond to an evasive movement so as to mitigate potential damage to the robot or to the collision object.

The inventors recognized that the proposed method, and in particular the proposed compilation of the components of the feature vector $\vec{M}$, allow a very precise and robust analysis and classification of the manner of action of an external force $F_{ext}$ as a desirable contact event or an undesirable contact event, so that the method makes the open-loop and/or closed-loop control of actuators of the robot possible with significantly improved consideration of environmental contacts, and in response thereto.

The analysis and classification of environmental contacts of the robot may advantageously be improved when the feature vector $\vec{M}$ additionally comprises the following components:

- a degree of the informational content, such as Shannon entropy or Shannon entropy distribution of G(t) in the time interval T; and/or
- one or more Hjorth parameters, such as the activity, mobility or complexity of G(t) in the time interval T; and/or

- one or more energy-related parameters of G(t) in the time interval T; and/or
- one or more autocorrelation-related parameters of G(t) in the time interval T; and/or
- one or more skewness parameters of G(t) in the time interval T; and/or
- one or more spectral phase parameters of G(t) in the time interval T; and/or
- one or more spectral amplitude parameters of G(t) in the time interval T.

Furthermore advantageously, the feature vector $\vec{M}$ can comprise parameters of two or more classifiers that are chronologically staggered with respect to one another, wherein the classifiers are also able to ascertain the parameters for different time intervals T.

The object of the invention is moreover achieved by a computer system comprising a data processing device, wherein the data processing device is designed in such a way that a method, as described above, is carried out on the data processing device.

Moreover, the object of the invention is achieved by a digital storage medium having electronically readable control signals, wherein the control signals can cooperate with a programmable computer system in such a way that a method, as described above, is carried out.

The object of the invention is furthermore achieved by a computer program product including program code stored on a machine-readable carrier for carrying out the method, as described above, when the program code is executed on a data processing device.

Finally, the invention relates to a computer program including program code for carrying out the method, as described above, when the program is executed on a data processing device. For this purpose, the data processing device can be designed as any arbitrary computer system known from the related art.

The aspect of the invention in terms of the device is achieved by a device for the open-loop and closed-loop control of actuators of a robot, taking environmental contacts into consideration, wherein the robot comprises at least two parts, which are connected by way of an articulated joint drivable by an actuator, comprising: a sensor system for ascertaining and storing a time-dependent variable G(t), which can be used to describe the action, as a function of the time, of one or more external contact forces $F_{ext}$ and/or of one or more external moments $M_{ext}$ on the parts, an interface for providing a condition B for this variable G(t), an evaluation unit, which is configured and designed in such a way that, provided that the condition B is not satisfied by G(t) at a time $t_0$, a feature vector $\vec{M}$ is ascertained for the detected variable G(t) over a time interval $T = [t_a, t_e]$, where $t_a$ = start of the time interval, $t_e$ = end of the time interval, $t_0 \in T$ and $t_0 < t_e$, the feature vector comprising the following components: a median or mean value of G(t) in the time interval T, a minimum and a maximum of G(t) in the time interval T, a deviation of G(t) from the median or from the mean value in the time interval T, a signal width of G(t) in the time interval T, a frequency spectrum of G(t) in the time interval T, and one or more characteristic frequencies of the frequency spectrum, a classification unit for classifying the feature vector $\vec{M}$ based on predefined categories of possible feature vectors $\vec{M}$ [illegible], which each indicate a contact type between the parts and an object in a surrounding environment, which are each imparted by corresponding external contact forces $F_{ext}$ and/or external contact moments $M_{ext}$, to generate a classification result KE, and a unit for the open-loop and closed-loop control of the actuator as a function of the classification result KE.

Sensors of the sensor system can advantageously be a combination of proximity sensors and force sensors, wherein force sensors are not necessarily able to distinguish between push and pull (whether a force is pulling or pushing results from the information as to the side of the body on which the force acts); in this case, for example, the proximity sensors could resolve this ambiguity.

Refinements and advantages of the proposed device are derived from a corresponding and analogous application of the comments provided for the proposed method.

Additional advantages, characteristics and details will be apparent from the description, which in detail describes at least one exemplary embodiment—where necessary, with reference to the drawing. Identical parts, similar parts and/or parts with equivalent functions have been denoted by the same reference numerals.

In the drawings:

FIG. 1 shows a flow chart of a method according to the invention; and
FIG. 2 shows a schematic composition of a device according to the invention.

FIG. 1 shows a flow chart of a method according to the invention for the open-loop and closed-loop control of three actuators of a robotic arm, taking environmental contacts into consideration, wherein the robotic arm in the present exemplary embodiment comprises four arm segments, which are connected in series by way of three articulated joints, each of which is drivable by one of the actuators. In the present exemplary embodiment, each of the three articulated joints moreover comprises a moment sensor for detecting moment measurement values $m_i(t)$, where i - 1, 2, 3. Over the course of time, each moment sensor thus detects a time series of measurement values $m_i(t)$.

In addition to the moment sensors, a sensor system comprises an evaluation unit and a memory unit. In a first step 101, the sensor system, based on the moment measurement values $m_i(t)$, in the present example ascertains a time-dependent total moment G(t) acting on the robotic arm.

The moment measurement values $m_i(t)$ generally do not yet directly yield the external total moment G(t) since inertial forces, Coriolis forces and gravitational forces still have to be considered. For this purpose, the external total moment G(t) generally first has to be estimated or at least (if acceleration sensors are present) algebraically ascertained.

The variable $G(t)$ is accordingly a scalar variable in the exemplary embodiment, which can be used to describe the action, as a function of the time, of one or more external contact forces $F_{ext}$ and/or of one or more external moments $M_{ext}$ on the robotic arm. Naturally, the variable $G(t)$ can also be multidimensional. In a simple multidimensional case, for example, $G(t) = G_i(t) = [g_1(t), g_2(t), g3(t)]^T = m_i(t) = [m_1(t), m_2(t), m_3(t)]^T$.

In a second step 102, a condition B for the variable $G(t)$ is provided, which in the present case is the condition $G(t) \leq F$. The condition B or the limiting value $F_i$ is selected such that the condition B is satisfied as long as no environmental contact with the robotic arm takes place, which is to say neither a desirable nor an undesirable contact event is present. The corresponding limiting value F may be ascertained in test series for this purpose, in which the robotic arm carries out random movements, without any environmental contact occurring. The closed-loop control of the actuators involves calibration steps which seek to improve the measurement or estimation of the external torques and/or external forces.

Provided that the condition B is not satisfied by $G(t)$ at a time $t_0$, which is to say environmental contact occurred, in a third step 103 a feature vector [illegible] $(G(t))$ is ascertained for the detected variable $G(t)$ over a time interval $T = [t_a, t_e]$, where $t_a$ = start of the time interval, $t_e$ = end of the time interval, $t_0 \in T$ and $t_0 < t_e$, the feature vector comprising all the following components:

- a median of $G_i(t)$ in the time interval T;
- a minimum and a maximum of $G(t)$ in the time interval T;
- a deviation of $G(t)$ from the median in the time interval T;
- a signal width of $G(t)$ in the time interval T;
- a frequency spectrum of $G(t)$ in the time interval T; and
- natural frequencies of the frequency spectrum.

In a fourth step 104, a classification of the feature vector $M$ (G(t)) takes place based on predefined categories of possible feature vectors $M$ to generate a classification result KE. The classification result KE thus indicates a specific contact category. The predefined categories of possible feature vectors $M$ are ascertained based on corresponding test series, for example, in which a wide variety of scenarios of environmental contacts are evaluated and divided into categories. These categories advantageously indicate different types of contact between one of the arm segments and/or the articulated joints and an object of a surrounding environment, which are imparted by external forces $F_{ext}$ and/or by contact moments $M_{ext}$.

In a fifth step 105, the open-loop and/or closed-loop control of the actuators for times $t > t_0$ take place as a function of the classification result KE. For this purpose, a specification for the open-loop and/or closed-loop control is provided for every classification result, such as in a look-up table. However, a relationship may also be achieved via mathematical formulas, such as by way of differential equations.

FIG. 2 shows a device for the open-loop and/or closed-loop control of actuators of a robot, taking environmental contacts into consideration, wherein the robot comprises at least two parts, which are connected by way of an articulated joint drivable by an actuator. The device comprises a sensor system 201 for ascertaining and storing a time-dependent variable G(t) which can be used to describe the action, as a function of the time, of one or more external contact forces $F_{ext}$ and/or of one or more external moments $M_{ext}$ on the parts, an interface 202 for providing a condition B for this variable G(t), an evaluation unit 203, which is configured and designed in such a way that, provided that the condition B is not satisfied by G(t) at a time $t_0$, a feature vector $M$ (G(t)) is ascertained for the detected variable G(t) over a time interval $T = [t_a, t_e]$, where $t_a$ = start of the time interval, $t_e$ = end of the time interval, $t_0 \in T$ and $t_0 < t_e$, the feature vector comprising the following components: a median or mean value of G(t) in the time interval T, a minimum and a maximum of G(t) in the time interval T, a deviation of G(t) from the median or from the mean value in the time interval T, a signal width of G(t) in the time interval T, a frequency spectrum of G(t) in the time interval T, and one or more characteristic frequencies of the frequency spectrum, a classification unit 204 for classifying the feature vector [illegible] (G(t)) based on predefined categories, which each indicate a contact type between the parts and an object in a surrounding environment, which are each imparted by corresponding external contact forces $F_{ext}$ and/or external contact moments $M_{ext}$, to generate a classification result KE, and a unit (205) for the open-loop and/or closed-loop control of the actuator as a function of the classification result KE.

List of Reference Numerals

101 to 105 method steps

201 sensor system
202 interface
203 evaluation unit
204 classification unit
205 unit for open-loop and/or closed-loop control of the actuators

## Patentkrav

**1.** Fremgangsmåde til styring og regulering af en robots aktuatorer under hensyntagen til omgivelseskontakter, hvor robotten omfatter mindst to dele, som er forbundet via en ledforbindelse, der kan drives ved hjælp af en aktuator, med følgende trin:
- ved hjælp af et sensorsystem fastslåelse og lagring af en tidsafhængig en- eller flerdimensionel størrelse G(t), hvormed den tidsmæssige indvirkning fra en eller flere eksterne kontakt-kræfter $F_{ext}$ og/eller et eller flere eksterne momenter $M_{ext}$ på delene kan beskrives,
- tilvejebringelse af en betingelse B for størrelsen G(t),
- såfremt betingelsen B ikke opfyldes af G(t) på et tidspunkt $t_0$, bliver der for den registrerede størrelse G(t) via et tidsinterval $T = [t_a, t_e]$, med $t_a$ = begyndelse på tidsintervallet, $t_e$ = afslutning på tidsintervallet, $t_0 \in T$ og $t_0 < t_e$ fastslået en kendetegnsvektor *M* (G(t)), som omfatter følgende komponenter:
- en median eller middelværdi af G(t) i tidsintervallet T,
- et minimum og et maksimum af G(t) i tidsintervallet T,
- en afvigelse af G(t) fra medianen eller fra middelværdien i tidsintervallet T,
- en signalbredde af G(t) i tidsintervallet T,
- et frekvensspektrum af G(t) i tidsintervallet T og
- en eller flere karakteristiske frekvenser af frekvensspektret,
- klassificering af kendetegnsvektoren *M* (G((t)) ved hjælp af på forhånd angivne kategorier, som angiver respektivt en kontaktform af en af delene eller ledforbindelsen med et objekt af omgivelserne, som kan respektivt fastslås ved tilsvarende eksterne kontakt-kræfter $F_{ext}$ og/eller eksterne kontaktmomenter $M_{ext}$, til generering af et klassificeringsresultat KE, og
- styring og/eller regulering af aktuatoren for tidspunkter $t > t_0$ afhængigt af klassificeringsresultatet KE.

**2.** Fremgangsmåde ifølge krav 1,
hvor kendetegnsvektoren *M* (G(t)) endvidere omfatter følgende komponenter:
- en Shannon-entropi eller Shannon-entropi-fordeling af G(t) i tidsintervallet T og/eller
- en Hjorth-parameter af G(t) i tidsintervallet T og/eller
- en eller flere energi-parametre af G(t) i tidsintervallet T og/eller

- en eller flere autokorrelationsparametre af G(t) i tidsintervallet T og/eller
- en Schiefe-parameter af G(t) i tidsintervallet T og/eller
- en eller flere spektrale fase-parametre af G(t) i tidsintervallet T og/eller
- en eller flere spektrale amplitude-parametre af G(t) i tidsintervallet T.

**3.** Fremgangsmåde ifølge krav 1 eller 2,
hvor begyndelsen $t_a$ på tidsintervallet T og afslutningen $t_e$ på tidsintervallet T er tidsafhængige $t_a = t_a(t)$ og $t_e = t_e(t)$ eller afslutningen $t_e$ på tidsintervallet T er tidsafhængig $t_e = t_e(t)$.

**4.** Fremgangsmåde ifølge et af kravene 1 til 3,
hvor robotten omfatter flere dele, som er forbundet via flere ledforbindelser, som kan drives ved hjælp af aktuatorer.

**5.** Fremgangsmåde ifølge et af kravene 1 til 4,
hvor størrelsen G(t) angiver en eller flere kræfter og/eller et eller flere omdrejningsmomenter og/eller en eller flere mekaniske spændinger og/eller et eller flere tryk.

**6.** Fremgangsmåde ifølge et af kravene 1 til 5,
hvor sensorsystemet omfatter mindst en sensor, som er anbragt på en af delene, med fladt anbragte sensorelementer til positionsfølsom registrering af eksterne kræfter $F_{ext}$ i forhold til delen, hvor størrelsen G(t) registreres på basis af de registrerede eksterne kræfter $F_{ext}$.

**7.** Fremgangsmåde ifølge et af kravene 1 til 6,
hvor sensorsystemet omfatter en omdrejningsmoment- og/eller kraft- og/eller accelerationssensor, som er forbundet med en af ledforbindelserne, til registrering af et omdrejningsmoment, som griber fat ved ledforbindelsen, og/eller en kraft, som griber fat ved ledforbindelsen, og/eller en acceleration, som griber fat ved ledforbindelsen.

**8.** Fremgangsmåde ifølge et af kravene 1 til 7,
hvor størrelsen G(t) fastslås respektivt for en eller flere af delene og/eller for

en eller flere ledforbindelser.

**9.** Fremgangsmåde ifølge et af kravene 1 til 8, hvor der afhængigt af klassificeringsresultatet sker en styring og/eller regulering af aktuatoren på en sådan måde, at en bevægelse af delene stoppes, gøres langsommere, accelereres, eller der indledes en bevægelse i modsat retning.

**10.** Indretning til styring og regulering af en robots aktuatorer under hensyntagen til omgivelseskontakter, hvor robotten omfatter mindst to dele, som er forbundet via en ledforbindelse, som kan drives ved hjælp af en aktuator, og til udførelse af en fremgangsmåde ifølge et af de foregående krav med:
- et sensorsystem til at fastslå og lagre en tidsafhængig størrelse G(t), hvormed den tidsmæssige indvirkning fra en eller flere eksterne kontakt-kræfter $F_{ext}$ og/eller et eller flere eksterne momenter $M_{ext}$ på delene kan beskrives,
- en grænseflade til tilvejebringelse af en betingelse B for denne størrelse G(t),
- en evalueringsenhed, som er udført og indrettet på en sådan måde, at såfremt betingelsen B ikke opfyldes af G(t) på et tidspunkt $t_0$ bliver der for den registrerede størrelse G(t) via et tidsinterval T = $[t_a, t_{e]}$, med $t_a$ = begyndelse på tidsintervallet, $t_e$ = afslutning på tidsintervallet, $t_0 \in T$ og $t_0 < t_e$, fastslået en kendetegnsvektor *M* (G(t)), som omfatter følgende komponenter:
- en median eller middelværdi af G(t) i tidsintervallet T,
- et minimum og et maksimum af G(t) i tidsintervallet T,
- en afvigelse af G(t) fra medianen eller fra middelværdien i tidsintervallet T,
- en signalbredde af G(t) i tidsintervallet T,
- et frekvensspektrum af G(t) i tidsintervallet T og
- en eller flere karakteristiske frekvenser af frekvensspektret,
- en klassifikationsenhed til klassificering af kendetegnsvektoren *M* (G((t)) ved hjælp af på forhånd angivne kategorier, som angiver respektivt en kontaktform af delene med et objekt af omgivelserne, som kan respektivt fastslås ved tilsvarende eksterne kontakt-kræfter $F_{ext}$ og/eller eksterne kontaktmomenter $M_{ext}$, til generering af et klassificeringsresultat KE, og
- en enhed til styring og/eller regulering af aktuatoren afhængigt af klassificeringsresultatet KE.

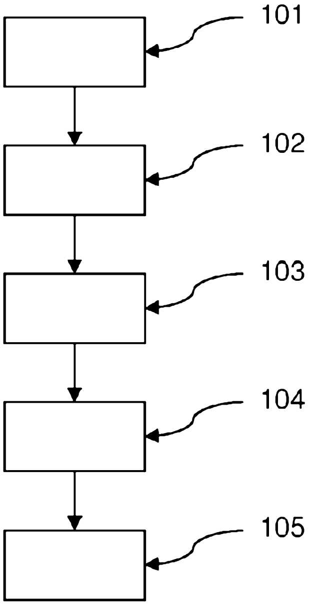


Fig. 1

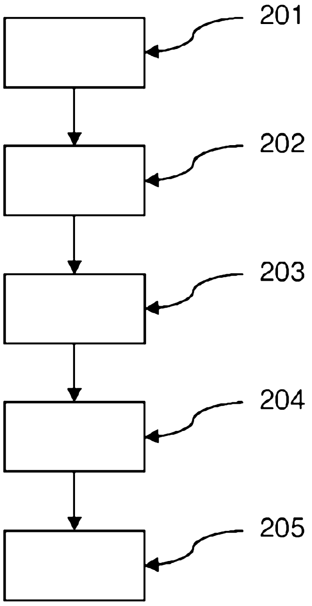


Fig. 2