Multi Agent Based Kinematics Solution Method for Multi Link Robot

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Abstract—This paper proposes a framework of a distributed kinematics resolution model which can be applied to various types of multi link robot structures. In the framework, hardware modules which consists of joints and links are defined as joint components of robotic systems, then kinematics resolution models are composed of a set of the local kinematics modules (LKMs) which are software modules to compute the localized direct and inverse kinematics corresponding to each joint component. Kinematics computation throughout the robotic systems is resolved by the localized kinematics calculation of LKMs for an end effector to a target position and an information exchange among LKMs. The proposed framework has been applied to case studies of the inverse kinematics problems of 7 degree of freedom multi link robot manipulator. Case studies have confirmed the proposed model to be able to provide a dexterous framework of manipulator. Case studies have confirmed the proposed framework has been applied to various types of multi link robot structures. In human life support, the working environment is not always in a situation. The surroundings of robots are exposed to a variety of creations and obstacles. Kinematics computation for this framework will be under the situation even more complicated and difficult in terms of utilizing and controlling in the application of human surroundings.

In order to deal effectively with these kinds of complication and difficulty, dexterity with robot systems is required to enable it to take behavior appropriate for the occasion. The conditional and/or environmental variation should be admitted as a normal condition inherent in robot work of human life environment. A fundamental mechanism of dexterity with robot systems should be discussed to induce the change of robot condition from the variation caused among the robot work. Because behavior appropriate for the occasion embodies a sort of dexterity as well as intelligent, and the basis of intelligent can be considered to make it possible to change oneself for the variation.

The purpose of this study is to develop a systematic methodology for dexterous robot system that takes control of itself with suitable for the occasion, and to evaluate the potential effectiveness of the method in improving the adaptability for the variation that would be appeared at the practical use of robot systems in human surroundings.

As the first approach for the purpose, this study investigates a framework of kinematics resolution for redundant robot systems by means of multi-agents system (MAS in short) concept. MAS concept can be defined as a system in which a set of subsystems autonomously organizes a well-balanced condition as the whole system in accordance with an interaction among the subsystems and with the situation of surroundings. This essence of MAS is a basis of the cooperation of a crowd or a group, therefore, many of MAS applications in robotics has been published for the task cooperation in terms of mobile robots[3][4]. The method in mobile robots, however, can not always hold in universal robot system which has the kinematics constraints. MAS based researches have been also studied for manipulator control[5][6][7], but the assumption that, for example sensors exist, has been provided to relieve the kinematics constraints. Despite of the kinematics constraint can not be disregarded, MAS based kinematics resolution is little discussed for universal or general robot systems.

This paper presents the framework of kinematics resolution system based on MAS concept and the detail design of the
agents as well as the kinematics computation sequence of the system. The feasibility with the possible impact of the improved robot systems is confirmed through the case studies.

II. AGENT BASED KINEMATICS RESOLUTION MODEL

A. Framework of kinematics solution model

Multi-linked robots are composed of the parts, such as effectors, links, and prismatic or rotational joints. Each of those has a kinematic role as that, for example, effectors evaluate work or work points, and links transmit the motion generated by joints to the other parts of manipulator. Especially, a pair of joint and adjacent link is a basis of the description of the kinematics properties[8]. This study considers effectors and the pairs of joint/link as an unit component, as illustrated in Figure 1, and corresponds the kinematics process called agent to the unit component. The kinematics resolution system then is constructed by assembling the agents in accordance with mechanical structure of robots.

There are two types of agents called Local Kinematics Module (LKM) and Effect Point Module (EPM). LKM is in charge of the kinematics process to be performed by the pairs of joint and link. LKM calculates the rotation angle corresponding to joints from the deviation between the target and the current position of effector, and transmits the joint motion to other LKM located at the tip side of robots. EPM represents the effector, and it calculates the deviation between the current position of effector and its target point instructed from the out of system.

As shown in Figure 1, the kinematics solution system is configured by associating with the Input/Output relation between LKMs and EPM, and the result of this, the system is an isolated system in which LKM and EPM processes are directed by the closed information flow. The kinematics solution is asymptotically obtained as the robot posture in respect to the effector target position.

The feature of this system is to not define explicitly overall direct kinematics model of the robots. Research activities have been published for modular type robots[9][10][11]. These approaches and the method proposed here have a similar characteristic in robot system to be constructed by the unit components. The almost every had provided the method to obtain explicitly the overall kinematics function. In this study, LKM and EPM execute partial kinematics calculation corresponding to the unit component. Overall kinematics resolution model or function is not formulated until LKM and EPM is related to the each other. Therefore, system is scalable for the reconfiguration of robots by detaching and/or attaching of the unit components. The system can be reconfigured by the addition or the remove of LKM if necessary. Additional EPM also enables the instructions of target position different from effector, i.e. the kinematics solution can be obtained not only for effector but also for another parts of robots.

B. Outline of local kinematics

The block diagram of LKM is illustrated in Figure 2. The Figure 2 represents LKM corresponding to the j-th joint from the base. LKM consists of main three parts which are called Local Direct Kinematics process, Local Inverse Kinematics process, and Joint State variables. The term “Local” refers these processes or variables to the limitation as for each joint so that LKM corresponding to joint j calculates the kinematics properties about joint j.

The Joint State variables are the data to represent joint condition. They are joint position \( p_j \), joint axis \( a_j \), and joint rotation angle \( \theta_j \). These values are initialized according to a preliminary position and posture of robots. The Local Inverse Kinematics process calculates the rotation angle to be moved for minimizing the deviation between the current position and the target position of effector. The calculation is no singularity problem in practical situations, and it is easy to assess the operation range of rotation angle because LKM is an identical process with respect to each joint. The Local Direct Kinematics process consists of two transform operations and a composition operation. If the joint located at the base side is rotated, the joint position and posture located at the tip side is transformed by the motion transmitted through the links. The transform operation performs the transformation of the Joint State variables in accordance with other joint motion located at the base side. The composition operation makes the synthetic motion by composing the motion of oneself and the synthetic motion generated through the previous joints. For example, the Joint State variables of joint j are transformed by the synthetic motion \( ^{1}R_{j-1} \) and \( ^{1}L_{j-1} \) which are rotation and translation, respectively. Where the motion of joint j is \( ^{1}R_{j} \) and \( ^{1}L_{j} \), the synthetic motion \( ^{1}R_{j-1} \) is made by composing the motion \( ^{1}R_{j-1} \) and the motion \( ^{1}R_{j}, ^{1}L_{j} \). This synthetic motion is then transformed to \( ^{1}R_{j} \), \( ^{1}L_{j} \).
motion is sent to next LKM, and it is composed one after another for transforming the Joint State variables of LKM located at the tip side.

EPM refers to effector and its process is the same as LKM in the composition except for the process to obtain the deviation between the current position and the target position of effector instead of Local Inverse Kinematics process. The current position of effector and the deviation are sent to all of LKM for invoking the Local Inverse Kinematics process.

C. Kinematics resolution process

The overall kinematics is executed by the successive approximations of LKM process for the deviation calculated by EPM.

The local direct kinematics of LKM transforms value of the Joint State variables based on synthetic motion \( ^1R_{j-1} \) and \( ^1L_{j-1} \). \(^1R_{j-1} \) and \( ^1L_{j-1} \) are the synthetic motion composed by LKM through from the base to joint j-1, for instance in Figure 3. The Joint State variables, therefore, are correctly transformed by each of LKM. The direct kinematics properties are satisfied for the overall robots. In example of the j-1 degrees of freedom robots, the EPM located at j-th from the base transforms the Effector State variables by \(^1R_{j-1} \) and \(^1L_{j-1} \).

On the other hand, the effector position \( P_E \) and the deviation \( \Delta P_G \) sent from EPM to each of LKM and the rotation angle is calculated to minimize the deviation by invoking the Local Inverse Kinematics process of LKM. The rotation angle accumulates as the joint angle \( \theta_j \) that is one of the Joint State variables. When the above processing is repeated at proper times, \( \Delta P_G \) is converged on zero and \( \theta_j \) is converged on a certain value. This joint angle \( \theta_j \) is the solution of inverse kinematics problem for the target position vector \( P_G \).

\(^1R_{j-1} \), \(^1L_{j-1} \), \( P_E \) and \( \Delta P_G \) are obtained from the base side LKM and EPM. Then, \(^1R_1 \) and \(^1L_1 \) can be determined from only the Joint State variables of oneself. Therefore, the direct kinematics of robots can be distributed by LKM. LKM is the same process for all joints. The kinematics resolution system can be composed by attaching or detaching LKM with the structure of robots and by initializing the Joint State variables.

III. LOCAL KINEMATICS CALCULATION

A. Local inverse kinematics

The Local Inverse Kinematics process calculates the deviation angle to minimize the distance between effector and target position by observing from a view of joint. The deviation angle can be represented by the magnitude of vector which is obtained as a joint axis projection of the deviation angle vector.

As shown in Figure 4, the deviation angle vector is a plane angle formed between \( g_j \) and \( e_j \). The deviation angle \( \Delta \theta_j \) is expressed in the following equation (1), where the joint position and axis are \( p_j \) and \( a_j (|a_j| = 1) \) respectively and the position of the effector is \( P_E \) and the vector of target deviation is \( \Delta P_G \).

\[
\Delta \theta_j = \begin{cases} 
0 & |e_j \times g_j| = 0 \\
B \cdot a_j \cos^{-1} C & |e_j \times g_j| \neq 0 
\end{cases} 
\]

Here, \( B = \frac{e_j \times g_j}{|e_j \times g_j|} \) and \( C = \frac{|e_j \times g_j|}{|e_j| \cdot |g_j|} \).

\( e_j = P_E - p_j \) and \( g_j = e_j + \Delta P_G \) are the information’s provided from EPM. Also, \( e_j = 0 \) and \( g_j = 0 \) give singular points of the equation (1), but it is the case of \( P_E + \Delta P_G = p_j \) or \( P_E = p_j \), hence singularity is not noticed in a practical range. Effector motion is generated as a sort of superposition of each joint motion. \( \Delta \theta_j \) is approximate value, and then if it is set for a rotation angle, effector does not possibly converge on the target position. So, an appropriate proportional constant \( K_j(< 1) \) is introduced, finally the deviation angle is calculated as \( K_j \Delta \theta_j \).

B. Local direct kinematics

The local direct kinematics transforms the Joint State variables of LKM in accordance with the synthetic motion sent from the base side LKM.

Here, \(^1R_{j-1} \) and \(^1L_{j-1} \) represent the synthetic motion composed from the base through to the joint j-1. The joint j transforms own Joint State variables by the motion. When the joint position is \( p_j \) and the joint axis is \( a_j \) before transformation,
by the motion of $^3\mathbf{R}_{j-1}$ and $^1\mathbf{L}_{j-1}$, the Joint State variables are transformed as follows.

$$\begin{align*}
\mathbf{p}_j &= ^1\mathbf{R}_{j-1}\mathbf{p}_j + ^1\mathbf{L}_{j-1} \\
\mathbf{a}_j &= ^1\mathbf{R}_{j-1}\mathbf{a}_j
\end{align*}$$  \hspace{1cm} (2)

After transformation, for new position $\mathbf{p}_j$ and axis $\mathbf{a}_j$, the rotation $\mathbf{R}_j$ represents as follow from Rodriguez equation when the joint $j$ rotate $\Delta \theta_j$.

$$\mathbf{R}_j = \mathbf{E} + [\mathbf{a}_j] \times \sin \Delta \theta_j + [\mathbf{a}_j \times ]^2 (1 - \cos \Delta \theta_j)$$  \hspace{1cm} (3)

Where, $\mathbf{E}$ is an unit matrix, $[\mathbf{a}_j \times ]$ is an alternating matrix which is satisfied $\mathbf{a}_j \times \mathbf{p} = [\mathbf{a}_j \times ] \mathbf{p}$ with an arbitrary vector $\mathbf{p}$. As shown in Figure 4, $\mathbf{a}_j$ is an axis of rotation passing through $\mathbf{p}_j$. The rotation generated by the joint $j$ with angle $\Delta \theta_j$ transforms an arbitrary point $\mathbf{p}$ and axis $\mathbf{a}$ as follows.

$$\begin{align*}
\mathbf{p}_j &= \mathbf{R}_j (\mathbf{p} - \mathbf{p}_j) + \mathbf{p} \\
\mathbf{a}_j &= \mathbf{R}_j \mathbf{a}
\end{align*}$$  \hspace{1cm} (4)

The transformation of $\mathbf{p}$ at equation (4) can be performed by only rotation $\mathbf{R}_j$ around the origin and translation $(\mathbf{E} - \mathbf{R}_j)\mathbf{p}_j$. Consequently, the motion $^3\mathbf{R}_j$ and $^1\mathbf{L}_j$ which are the composition of $\mathbf{R}_j$, $(\mathbf{E} - \mathbf{R}_j)\mathbf{p}_j$ and $^1\mathbf{R}_{j-1}$, $^1\mathbf{L}_{j-1}$ is as follows.

$$\begin{align*}
^3\mathbf{R}_j &= {^1\mathbf{R}_j}{^3\mathbf{R}_{j-1}} \\
^1\mathbf{L}_j &= {^1\mathbf{R}_j}{^1\mathbf{L}_{j-1}} + (\mathbf{E} - \mathbf{R}_j)\mathbf{p}_j
\end{align*}$$  \hspace{1cm} (5)

From equation (3) and (4), $\mathbf{R}_j$ and $(\mathbf{E} - \mathbf{R}_j)\mathbf{p}_j$ are determined by only Joint State variables of joint $j$. If $^1\mathbf{R}_{j-1}$ and $^1\mathbf{L}_{j-1}$ are received from LKM located at the base side, highly independent MAS based kinematics resolution system is available for various structure robots.

IV. CASE STUDIES

A. Kinematics solution of 7 d.o.f manipulator

To investigate the proposed framework, the inverse kinematics problem of 7 d.o.f manipulator is executed about the end effector position as illustrated in Figure 5. The initial Joint State variables are show in Figure 5. All of joint angles are set zero at the initial posture, and then the end effector is placed on the position $(400, 400, 0)$.

The initial and the result posture are shown in Figure 6. For the iterative calculation by direct and inverse kinematics, the transition of each joint angle is shown in Figure 7. Firstly, some of joint angles had a big transformation, then these gradually converged a steady value as illustrated in Figure 7. The transition of position error between the end effector position and the target position is shown in Figure 8. This position error gradually gets smaller, after 23 times iteration processes it is less than 1 mm. This case study indicated possible to solve the inverse kinematics problem by the
proposed framework.

B. Case of error caused by assembling

The manipulator shown in Figure 5 has a structure where adjacent joint axes overlap each other at one point. In the second case study, the proposed method is applied to more universal case. This proposed method can be configured the kinematics system of any type of robots. As an example, in the case of that joint five is mounted with a tilt, the inverse kinematics has been calculated. The Joint State variables of each joint are shown in Table 1. The transition of each joint angles in the iteration process is shown in Figure 9. The transition of position error is shown in Figure 10. These results show that it is possible to solve the kinematics resolution for the various type of manipulator.

C. Specifying target position for multiple locus

In this proposed method, the various locus in the manipulator can be set as the target position same as the end effector. In the following simulation, the kinematics calculation is executed on giving the target positions to the end effector and elbow joint respectively. The four joint, J4, J5, J6, J7 are concern with the end effector, the three joint, j1, j2, j3 are concern with the elbow joint. The target position for end effector is the same as noted above. EPM is added on the joint 4, and the target position for elbow joint is (35.0,395.0,-12.0). The initial posture and the result posture are illustrated in Figure 11. It is determined that the elbow joint is lifted up and the end effector is on the reference position. Each joint angle for the iteration process is shown in Figure 12. 01 and 03 are vibrated behavior at early stage. Then, they are converged to state values. The reason for the vibration is that the joint of 01, 03 compete for the motion of joint 4 and the motion of end effector. Here, the EPM is not always have to be related a structural point of the manipulator. The point on a link or the virtual point on a space is available.

V. CONCLUSION

This paper has presented the framework of kinematics resolution system based on MAS concept and the detail design of the agents as well as the kinematics computation sequence of the system. The feasibility with the possible impact of the improved robot systems has been confirmed through the case studies. Conclusions are as follows.

1) Considering a module constructed from joint and link component of robot, defining the Local Kinematics Module (LKM) related to the component and the Effect Point Module (EPM) related to end effector, and the configuration method of a decentralized kinematics calculation model composed of LKM and EPM has proposed.

2) Implementability of decentralizing the calculation of LKM and EPM with respect to each module and calculating the direct and inverse kinematics of manipulator by iterative calculation has been shown.

3) The proposed method has been applied to the inverse kinematics problem of 7 d.o.f manipulator. The computability of the kinematics solution using the proposed calculation model and flexibly with various tasks has been shown.
In this proposed method, as the LKM and EPM are connected in series, the kinematics calculation model of serial link type robot can be configured. For a structural change, for example addition of an attachment, the kinematics calculation model can be configured only adding and inserting the LKM. The LKM corresponds to each joint module, the advantages of this method is easy to configure the specific character as range of rotation for each joint. Using multiple EPM, the inverse kinematics calculation for the various points except the end effector is capable. Inverse kinematics for the obstacle avoidance and the position in the narrow space are applied. As the inverse kinematics calculation in the LKM is executed only for connected EPM, a configuration of the kinematics calculation is made more flexible in accordance with task. In the case studies, a proportional constant is same value in all localized inverse kinematics. Depending on the proportional constant value, final pose of robot is changed. Proportional constant value and pose of robot, the amount of iteration times are required.

REFERENCES