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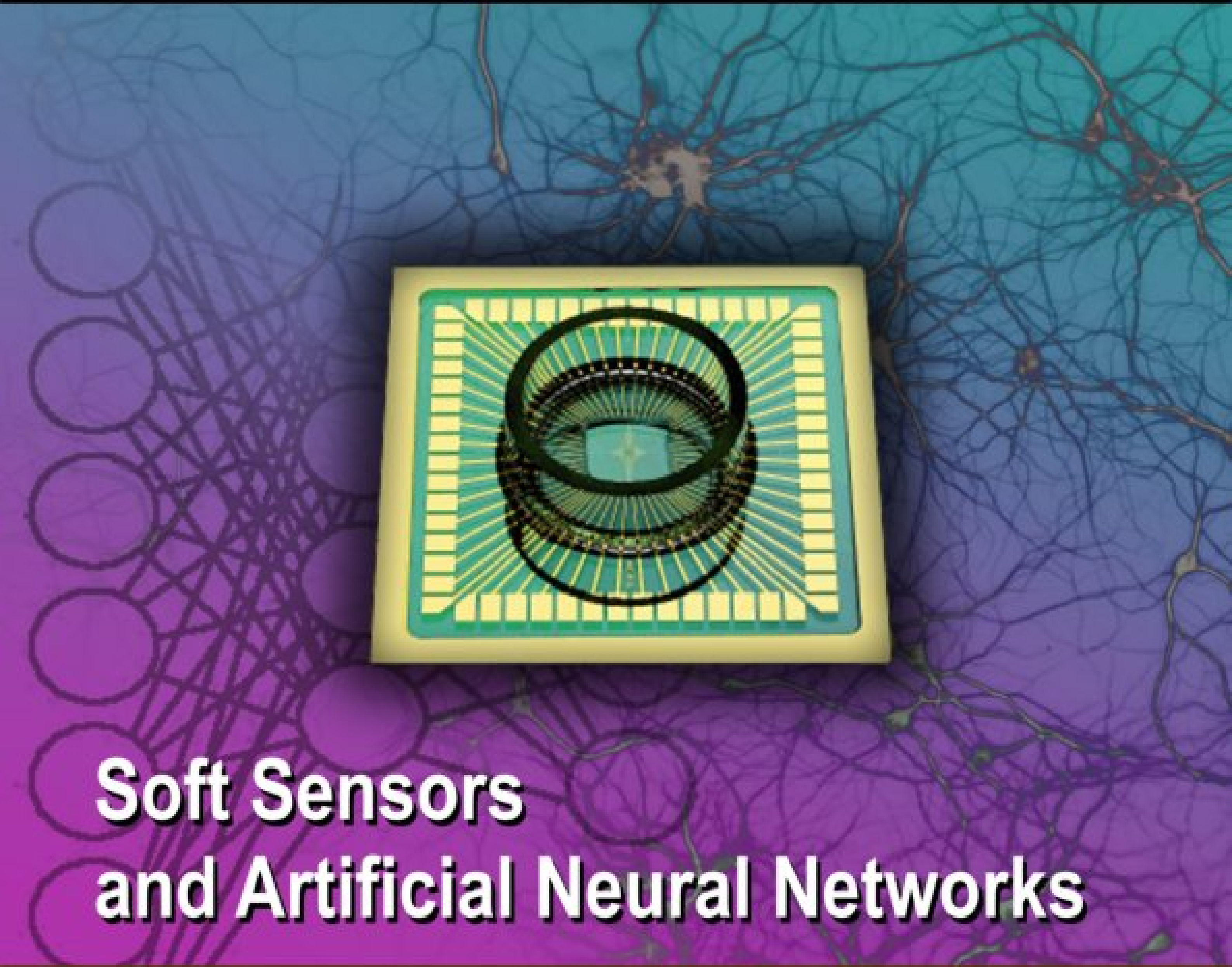

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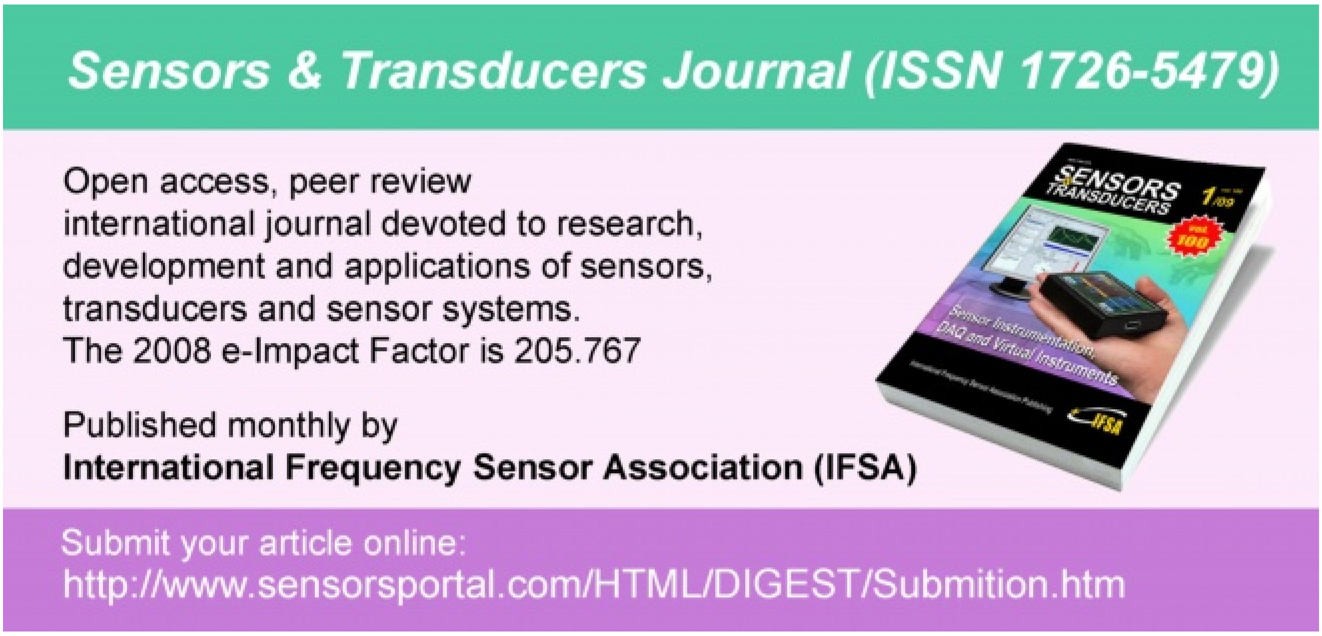

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Camera ready	March 20, 2011

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Improved RBF Neural Network Based Soft Sensor: Application to the Optimal Robust Calibration of a Six Degrees of Freedom Parallel Kinematics Manipulator

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Abstract: Accuracy is paramount for the further development of parallel mechanism in real world, especially in industry. Previous research was focused on the improvement of rigidity and load capacity which is related with the stiffness matrix of closed loop kinematic structure. However, if the mechanical structure has been predefined or fabricated, stiffness matrix only can search for the optimal configuration in the workspace, but fails to enhance the accuracy at a given pose. In this research, the concept of optimal robust calibration is developed as an effective approach to largely reduce various errors of the predefined parallel mechanism. A novel coevolutionary radial basis function (RBF) neural network based soft sensor is proposed to implement the optimal robust calibration procedure. A six-degrees-of-freedom parallel kinematics manipulator is selected as the case study to verify the proposed methodology. The results demonstrate that the coevolutionary neural network possesses the excellent performance as a smart soft sensor for the calibration of closed loop kinematic structure. *Copyright © 2010 IFSA.*

Keywords: Coevolutionary RBF neural network, Soft sensor, Optimal robust calibration, Black box, Parallel kinematics manipulator.

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1. Introduction

Parallel mechanisms have become an irreversible trend for the development of modern mechanism theory. Many application fields including robotic manipulators, reconfigurable manufacturing systems, physical sensors, bio-inspired robots, and pose adjusting devices have benefited from the inspiration of closed loop kinematic structures [1-8]. To highlight the importance of such mechanism, researchers call it "Parallel Kinematics Manipulator", which is abbreviated as PKM in many literatures. For industrial entities, it is not a question of whether they will recognize parallel manipulator, but how to improve its performance and make it more robust in different kinds of environments and tasks.

As is well known, accuracy is the most critical performance index of PKMs [9-16]. Castañeda and Takeda [12] investigated the path accuracy of parallel mechanisms and found that both the mechanical design and the control law contributed to the minimization of motion error. Briot and Bonev [13] found that if the four degrees of freedom (DOF) 3T1R fully-parallel robot was far from singularities, the related position errors happened only when the input variables suffered a maximal error. Noll *et al.* [15] developed a multiaxis positioning stage with high load capacity. The PKM topology based on trapezoidal arrangements was introduced that the output accuracy reached nano-level.

The singularity of PKMs can be avoided by 1) designing the singularity-free mechanism, and 2) replanning the dexterity path in the workspace. Similarly, the accuracy also can be controlled by 1) revisiting the stiffness matrix through the reconfiguration of PKM with modular sub-systems, and 2) searching the optimal stiffness path in the workspace. However, calibration is necessary if the mechanical systems have already been well designed. Furthermore, stiffness matrix is powerless to improve the operational or motion accuracy in a specific configuration. Soft sensor, which is also noted as virtual sensor, is usually a kind of algorithm that is packaged as the software. Together with of external or inner measuring instruments, soft sensor plays an important role in various applications [17-19].

In this paper, a new coevolutionary RBF neural network is proposed as a unique virtual sensor that is applied for the optimal robust calibration of a six-DOF PKM. In what follows, the principle and methodology of optimal robust calibration of parallel manipulators is developed in Section 2. The general idea, topology architecture, algorithm fundamental and detailed working steps of coevolutionary radial basis function (RBF) neural network as the soft sensor are proposed in Section 3. A type of fully symmetrical six-DOF PKM is introduced in Section 4. The algorithm implementation and results analysis are conducted in Section 5. Conclusions are given in Sections 6.

2. Optimal Robust Calibration of Parallel Manipulators via Soft Sensor

Different with the traditional physical or chemical sensors, the soft sensors have no the real instruments for information acquisition. In many cases, soft sensors severed as a kind of special algorithm to integrate, recognize and synthesize different characteristics of external signals. Soft sensors have the essential function in many real world applications. For instance, Kalman filters as a representative soft sensor have been widely utilized in fault diagnosis [20, 21].

As mentioned above, calibration is an indispensable procedure for the predefined parallel manipulators to guarantee their operational accuracy with/without external loads. Fig. 1 illustrates the architecture of accuracy enhancement for parallel manipulators in cases of undefined and predefined designs. Firstly, if the PKM is undefined, the idea of "Design for Required Accuracy" will be applied to satisfy the accuracy standard. Especially, if modularization is feasible, which means the PKM is constituted by several separated modules, structural reconfiguration will be conducted. In this scenario, the PKM works as a transformable robot whose function and performance is changed after reconfiguration. Secondly, if the PKM has already been predefined, the method of stiffness trajectory replanning can be implemented to search the ideal motion path of end-effector. In the singularity-free region, the optimal stiffness renders the optimal accuracy. In the case of specific pose, calibration with external/internal sensor or soft sensors is necessary.

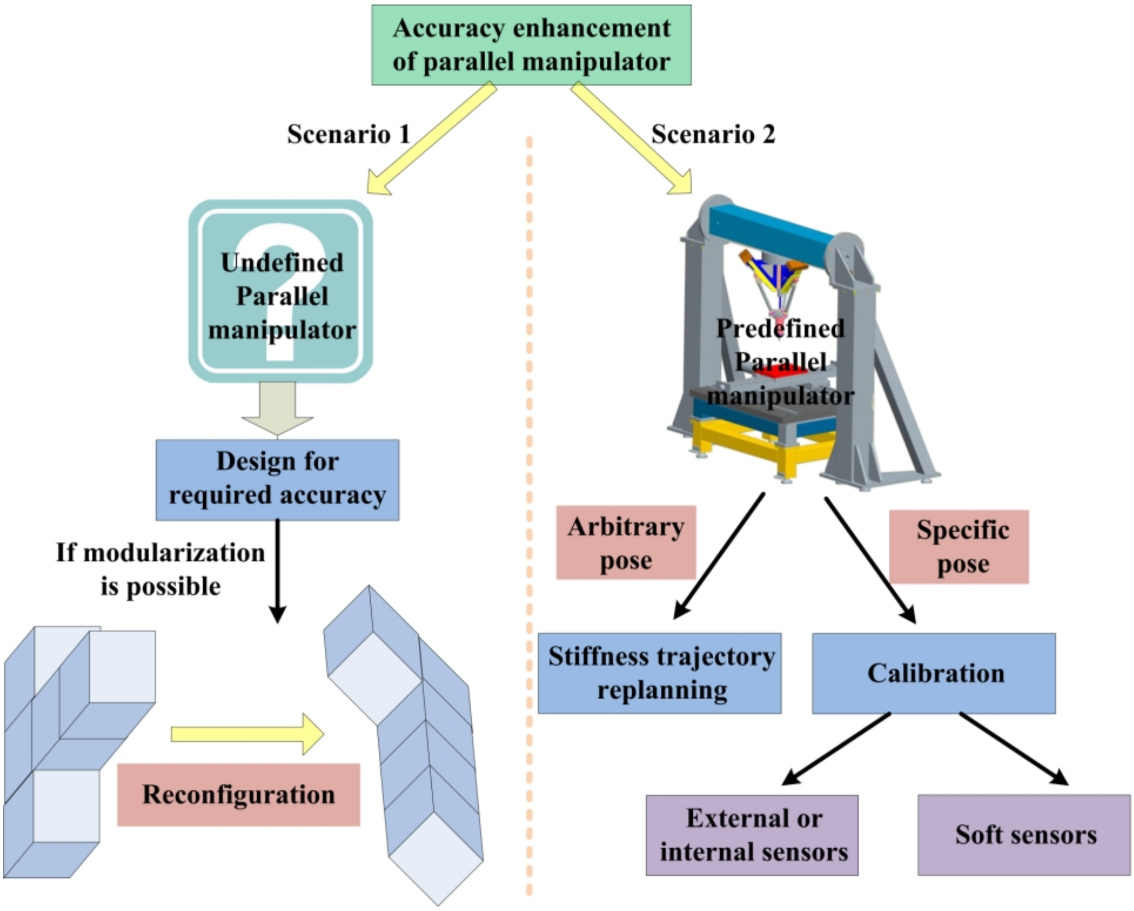


Fig. 1. The architecture of accuracy enhancement of parallel manipulator in undefined and predefined scenarios.

However, different with the calibration of simple devices or systems such as force/torque sensor, as a complex kinematic system, the calibration of PKM is very complicated. Usually, a completed kinematics calibration of PKM will cost several hours, even several days in some special cases. There are three main reasons,

1) It is difficult to find the sensitivity regions in the workspace or the reasonable configurations of the mechanical system.
2) The error of end-effector is affected by many factors including thermal effect, manufacturing tolerance, joint wear, and supporting environment. The external and internal sensors cannot acquire and recognize, and classify all of the error patters.
3) It is difficult to compensate the error of end-effector through adjusting the control parameters, since PKM is actuated by several independent kinematic chains. How to build the relationship of the compensated control parameters and the bias of end-effector is still an open problem.

The concept of optimal robust calibration is proposed based on the following definitions.

Definition 1*:* If one calibration algorithm can guarantee the optimal output accuracy of end-effector, then it is called optimal calibration;
Definition 2*:* If one calibration algorithm is not affected by the external disturbance and internal coupling, and it is appropriate for different types of parallel manipulator, then it is called robust calibration;
Definition 3*:* If both of the above definitions are satisfied, then it is called optimal robust calibration.

Fig. 2 explains the principle of the optimal robust calibration, which is the integration of optimal calibration and robust calibration. Because the PKMs have many error sources, it is almost impossible to sense different characteristic signals that are associated with the corresponding error source. Therefore, the theory of "black box" can be adopted here. All of the error sources are imbedded in the black box. The optimal robust calibration will bridge the relationship between control parameters and pose of end-effector without considering the detailed effect of each error source. The mapping matrix from task space to the tool task will be reconstructed after the accomplishment of the optimal robust calibration.

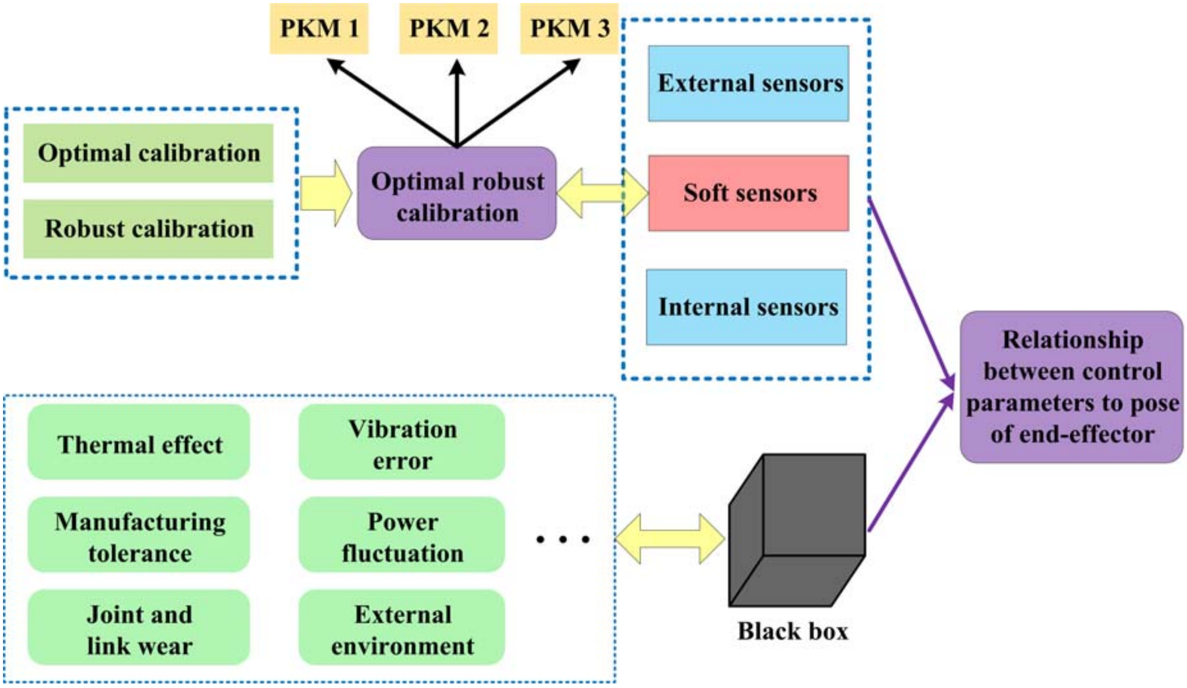


Fig. 2. The principle of optimal robust calibration.

3. Coevolutionary RBF Neural Network Based Soft Sensor

3.1. Background of Neural Network Based Soft Sensor

Artificial neural networks have become the popular research tools for the development of smart soft sensors in recent years [22-26]. In [22], the neural network based soft sensor was designed for real-time prediction of the olive pomace's moisture and fat content. In [23], a soft sensor based on the time-delayed recurrent neural network was developed for determining the degree of cure. Fileti *et al.* declared that the neural network based soft sensor was a reliable tool to solve on-line operational issues of the control systems [24]. Fortuna *et al.* applied the bootstrap resampling approach to inject the noise into the available information to conquer the problem of shortage of experimental data for the training and generalization of neural network based soft sensors [25]. In [26], particle swarm optimization fuzzy neural network was investigated as a kind of soft-sensor to monitor the acrylonitrile yield.

For the traditional neural networks, the simultaneous optimization of weights and nodes connecting is difficult, that largely affects the running efficiency including the time cost and convergence precision. In this study, a novel coevolutionary RBF neural network will be proposed as an efficient soft sensor that is capable of the optimal robust calibration of the general parallel manipulators.

3.2. Coevolutionary RBF Neural Network

RBF neural network has one type of typical feed-forward topologies. Similar with the conventional feed-forward neural networks with sigmoid transfer function, RBF neural network is constituted by three layers, the input layer, the hidden layer and a linear output layer [27, 28]. The main difference of RBF neural network with the traditional feed-forward neural networks is that it has a radial basis function, i.e. Gaussian function. The representative topology of a conventional RBF neural network is shown in Fig. 3.

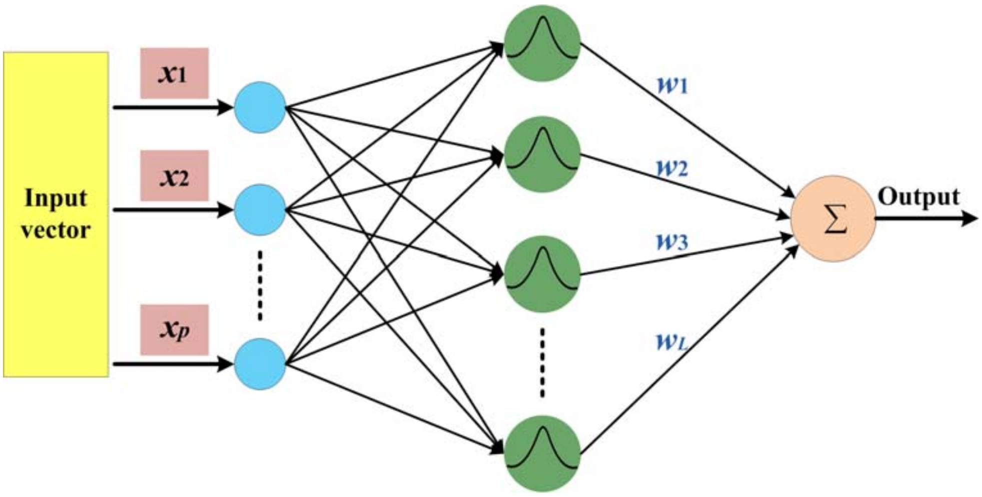


Fig. 3. The representative topology of a conventional RBF neural network.

Suppose that there is input vector $\boldsymbol{x}^r$, the corresponding output of j^{th} hidden node is expressed as

$$\phi_j(\boldsymbol{x}^r, \boldsymbol{c}_j) = \phi_j(\|\boldsymbol{x}^r - \boldsymbol{c}_j\|) , \tag{1}$$

where, $\phi_j(\cdot)$ is the radial basis function, $\boldsymbol{c}_j$ is the center associated with the hidden node j, $\|\boldsymbol{x}^r - \boldsymbol{c}_j\|$ is a norm of $\boldsymbol{x}^r - \boldsymbol{c}_j$ that is usually Euclidean distance, which denotes the distance between the input vector $\boldsymbol{x}^r$ and $\boldsymbol{c}_j$. If Gaussian function is applied as the radial basis function, Eq. (1) can be rewritten as

$$\phi_j(\boldsymbol{x}^r, \boldsymbol{c}_j) = \exp(-\frac{\|\boldsymbol{x}^r - \boldsymbol{c}_j\|_2^2}{2\sigma^2}) \tag{2}$$

If the number of hidden neurons is L, the total output for the input vector $\boldsymbol{x}$ is derived as,

$$y(\boldsymbol{x}) = \sum_{j=1}^{L} w_j \cdot \phi(\|\boldsymbol{x} - \boldsymbol{c}_j\|) = \sum_{j=1}^{L} w_j \cdot \exp(-\frac{\|\boldsymbol{x}^r - \boldsymbol{c}_j\|_2^2}{2\sigma^2}) , \tag{3}$$

where w_j is the weight between the j^{th} hidden neuron connecting to the output node.

The principle of coevolutionary RBF neural network is based on the integration of coevolutionary algorithm and RBF neural network (as shown in Fig. 4). The detailed algorithm is given as follows:

A) From the output to the input of the neural network, the connecting between hidden node *j* and output node, the corresponding weight w_j, and the connecting between hidden node *j* and input nodes are grouped as the *j*th subpopulation.

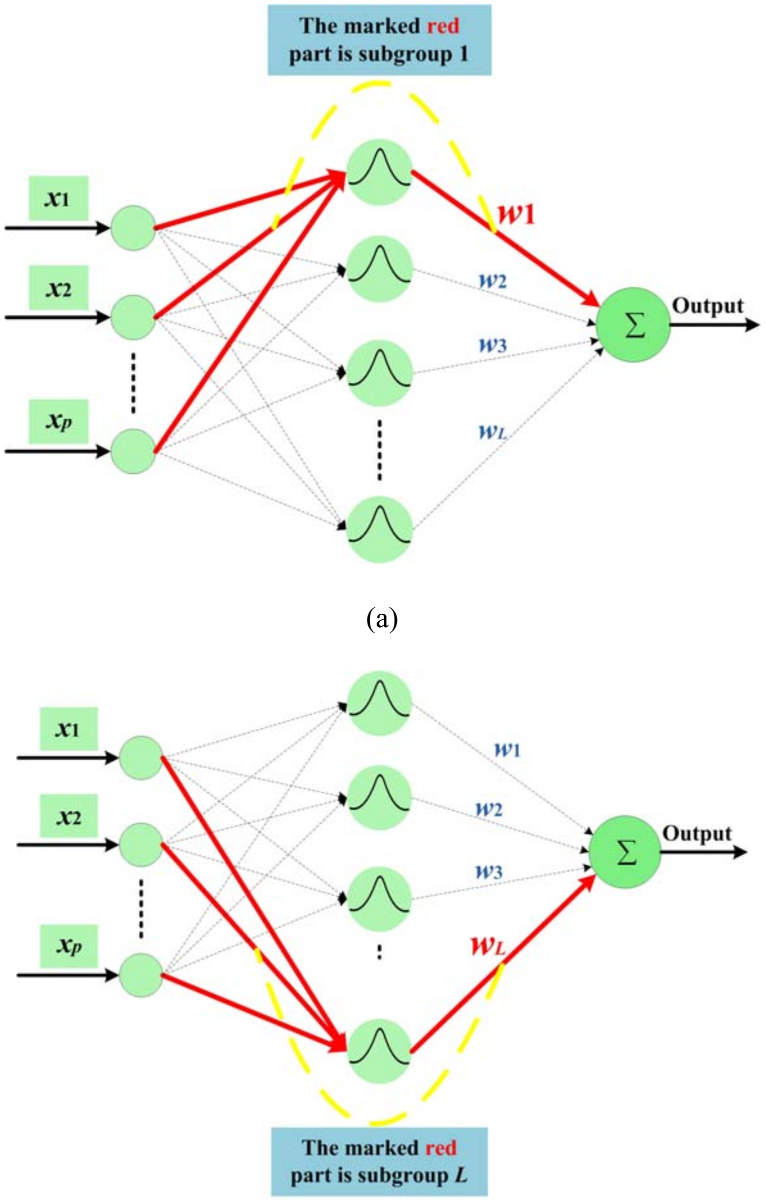
B) Initialize all of the subpopulations $\boldsymbol{s} = \mathrm{s}(1) + \mathrm{s}(2) + \cdots + \mathrm{s}(j) + \cdots + \mathrm{s}(L)$. The total number of the subpopulations is L.

C) Assess the fitness value through the cooperation of all the subpopulations. The fitness value is associated with the error cost function. All of the subpopulations constitute the complete RBF neural network to calculate the error cost function.

D) Implement the operators of selection, crossover and mutation for the subpopulation to create new subpopulation of next generation.

E) Each of the subpopulation conducts the genetic operation including selection, crossover and mutation. Select the best individual in each subpopulation to constitute a new complete RBF neural network and calculate its error cost function again.

F) If the convergence conditions are satisfied, then stops. Otherwise, go back to phase D.



(a)

(b)

Fig. 4. The segmentation of subgroup of coevolutionary RBF neural network; (a) the 1st subgroup, (b) the L^{th} subgroup; each subgroup contains the node connecting and corresponding weight.

4. Case Study

4.1. A Symmetrical Six-DOF PKM

MOOG 2000E motion platform is a successful application of the fully symmetrical 6-DOF PKM. It has the powerful potentials to be applied in aircraft simulation, pilot training, and virtual reality of vehicle motion. The prototype as shown in Fig. 5 is now located in the Robotics and Automation Laboratory, University of Ontario Institute of Technology, Canada. This 6-DOF PKM has the following features:

1) Actuated by six identical DC servomotors to control the six active prismatic joints in each independent limb.
2) It can generate the flexible motion in pitch, roll, yaw, heave, surge, and sway with excellent dynamic characteristics.
3) Emergency stop is available for actuator brake. Stroke limit switches are also equipped.
4) High payload capacity (maximal external payload is about 1000 Kg)
5) Remote monitor and manipulation is available based on Ethernet communication.
6) The ballscrew design of actuators can improve the accuracy and reduce the friction.

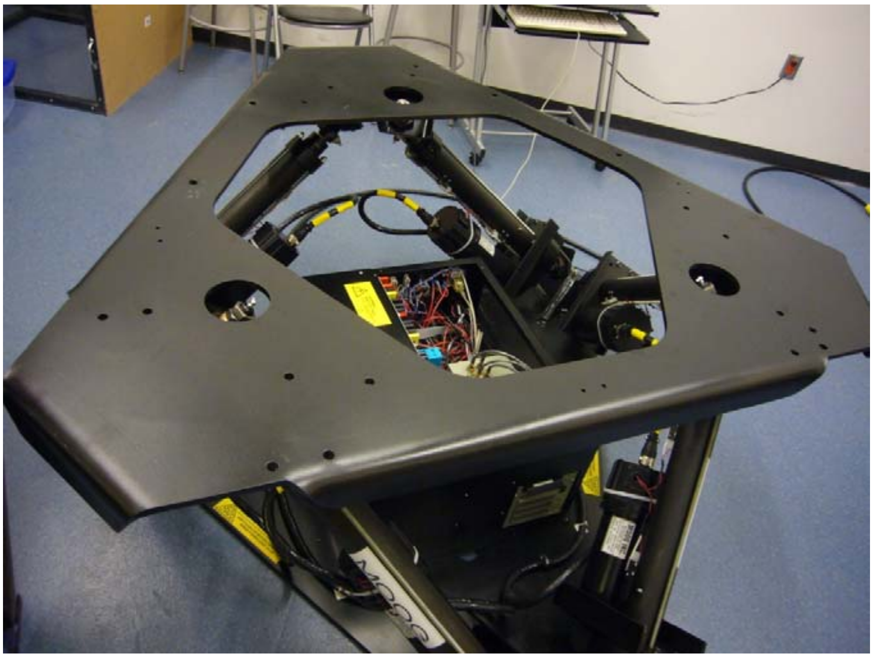


Fig. 5. The Prototype of MOOG 2000E motion platform.

Fig. 6 illustrates the electromechanical connection of the symmetrical 6-DOF PKM. Six identical prismatic joints from $SPLC_1$ to $SPLC_6$ work in parallel to drive the moving platform.

4.2. Implementation and Results

Two coordinate frames, O-XYZ and O′- X′Y′Z′ are attached to the base and the moving platform, respectively. The line OX is connected to the midpoint of $b1b2$, and the angle between line O$b1$ and OX is equal to θ_1. Similarly, the line O′X′ is connected to the midpoint of $p1p2$, and the angle between line O′$p1$ and O′X′ is equal to θ_2 (Fig. 7).

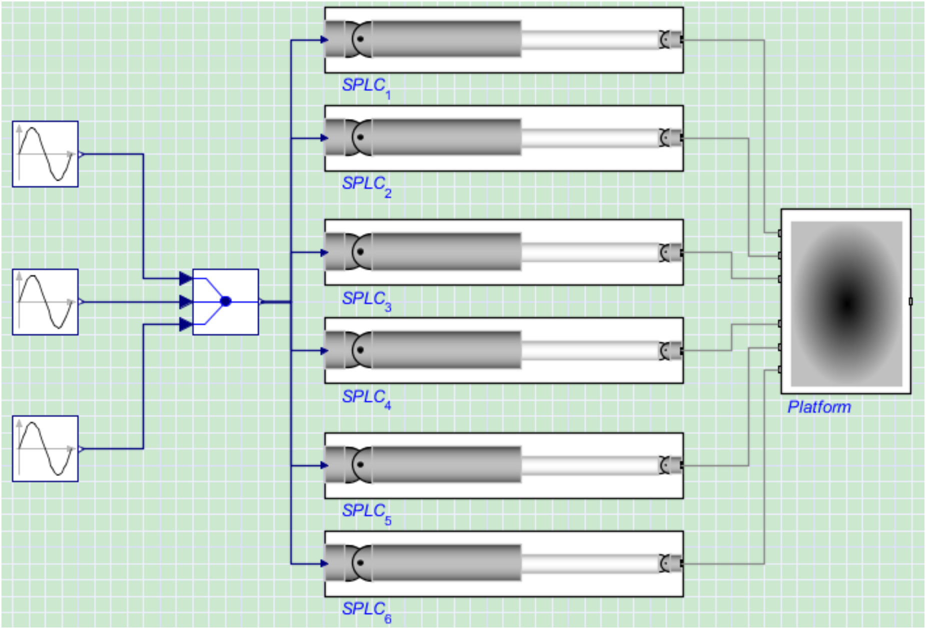


Fig. 6. The electromechanical connection of the whole system.

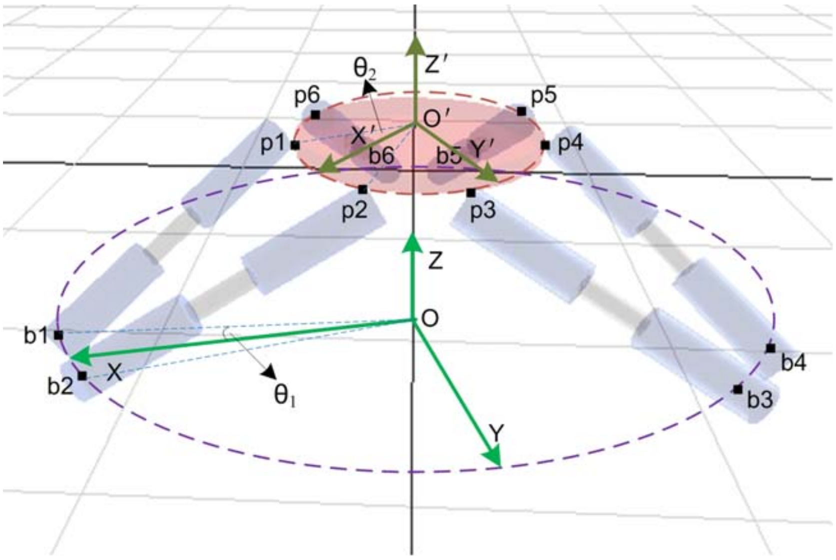


Fig. 7. The geometrical structure in construct mode.

It should be noted that inverse kinematics is necessary to implement the procedure of optimal robust calibration. Because we have done the related work in [29] for solving the inverse kinematics of a parallel manipulator with six degrees of freedom, only the general expression of the inverse kinematics for the symmetrical six-DOF PKM will be given here,

$$\rho_i = \sqrt{(\boldsymbol{p}_i - \boldsymbol{b}_i)^T (\boldsymbol{p}_i - \boldsymbol{b}_i)},\ i = 1,\ldots,6\ , \tag{4}$$

where, ρ_i is the length of the i^{th} leg, i.e., the value of the i^{th} joint coordinate, $\boldsymbol{p}_i$ is the position vector of point p_i with respect to the fixed coordinate frame, and $\boldsymbol{b}_i$ is the position vector of point b_i with respect to the fixed coordinate frame.

As mentioned in Section 2, all of the errors sources can be viewed as an error generator in a black box.

Supposed that the error generator induce the excursion of each actuated joint, the coevolutionary RBF neural network will learn the unpredicted relationship between the black box and the accuracy error of end-effectors. Suppose that the errors of control parameters for the six actuated joints are expressed by the following different error generators,

$$\Delta\rho_1 = N(u=0, \sigma=10^{-3}); \tag{5}$$

$$\Delta\rho_2 = 10^{-2} / \left(1+4\times e^{-t}\right); \tag{6}$$

$$\Delta\rho_3 = 1.4\times10^{-2} - 10^{-3}\cos(0.5\pi t); \tag{7}$$

$$\Delta\rho_4 = 0.8\times N(u=10^{-4}, \sigma=6\times10^{-3}); \tag{8}$$

$$\Delta\rho_5 = -10^{-4}\cos(\pi t\times random[0,1]); \tag{9}$$

$$\Delta\rho_6 = 10^{-3}\cos(0.5\pi t) - 4.6\times10^{-5}\cos(6\pi t); \tag{10}$$

Accordingly, 729 poses in the workspace will be chosen as the sample points, in which 400 samples are applied for training, the left 329 samples are applied for generalization and verification. The input dimensions of the coevolutionary RBF neural network are 6. The initial nodes number of the hidden layer is 20. The size of each subpopulation is 120. The maximal evolutional generations of each subpopulation are 300.

To verify the capacity of network generalization for the error compensation for the symmetrical 6-DOF PKM, the standard RBF neural network is used for results comparison. The mean square error (MSE) with the standard RBF neural network after training is $mse\_\rho_1 = 6.0513\times10^{-6}$, $mse\_\rho_2 = 5.3377\times10^{-6}$, $mse\_\rho_3 = 6.0915\times10^{-6}$, $mse\_\rho_4 = 4.2581\times10^{-6}$, $mse\_\rho_5 = 3.3810\times10^{-6}$, and $mse\_\rho_6 = 4.9397\times10^{-6}$. On the other hand, the MSE with coevolutionary RBF neural network after training is $mse\_\rho_1' = 8.0787\times10^{-7}$, $mse\_\rho_2' = 7.8523\times10^{-7}$, $mse\_\rho_3' = 8.9048\times10^{-7}$, $mse\_\rho_4' = 7.9896\times10^{-7}$, $mse\_\rho_5' = 9.4301\times10^{-7}$, and $mse\_\rho_6' = 1.3208\times10^{-6}$. The average accuracy of standard RBFN is 5.0099×10^{-6}, and average accuracy of coevolutionary RBFN is 9.2439×10^{-7}. The simulation results show that the improved algorithm has a significant accuracy enhancement of a factor about 5.4197.

6. Conclusions

Since accuracy is a very important factor for the application potential of PKM, improving the accuracy with the support of soft sensor is an effective approach, especially for the PKMs whose structures have already been confirmed. The integration of optimal calibration and robust calibration is proposed as an effective approach to largely reduce the operational error of end-effector without considering the detailed error sources. As an improved algorithm, the coevolutionary radial basis function is applied on a fully symmetrical six-DOF parallel manipulator as a kind of smart soft sensor. The results demonstrate that the proposed methodology is feasible for the kinematics calibration and error compensation of the general parallel kinematics manipulator. For the future work, an integrated error calibration system will be built based on the proposed methodology and the external/internal sensors to improve the dynamics accuracy of the MOOG 2000E motion platform.

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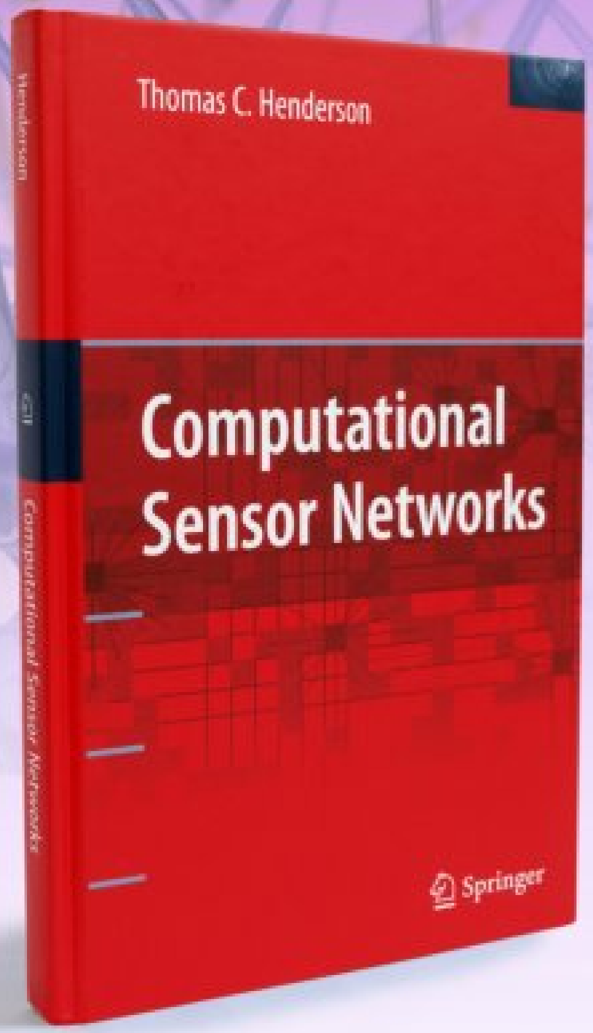
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