**Control and Calibration of Redundantly Actuated Parallel Robots**

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**Abstract**

The principle of redundant actuation described in other proposed papers enables to significantly improve the mechanical properties of parallel machines (dexterity, dynamics, stiffness, kinematic accuracy). However, from the point of view of machine control it represents a great challenge. There have been investigated two strategies: cooperation control and antagonistic control. The achieved results are described. It ranges from antagonistic dynamic increase of stiffness, antagonistic anti-backlash control through cooperation advanced control based on model predictive, inverse dynamics and sliding mode control approaches to the direct local PID drive control. The danger of undesired antagonistic behavior is analyzed and principles of required coordination are described.

The other great challenge of redundant actuation of parallel machines is the principal possibility to provide full on-line calibration. There have been investigated such approaches and the encountered computational problems for real redundantly actuated parallel machines based on practical computational and experimental experience are described.

## 1. Introduction

The parallel kinematic structures have many advantages, however also several severe disadvantages: generally smaller workspace, often presence of singular positions within workspace, often collisions of robot links. These drawbacks of parallel structures could be removed by the principle of redundant actuation [1, 2].

This principle states that the platform is supported and driven by more legs than the necessary number of DOFs. It is based on the following idea. One of the severe problems of parallel robots is the limitation of workspace especially due to the occurrence of singularities. If the platform of parallel robot is supported on the redundant number of legs (links, bars), i.e. on more than the needed number of DOFs - in plane on more than 3, in space on more than 6, then the following simplified consideration can be realised. If the certain combination of 6 legs from the redundant number of legs in the given position of the robot leads to a singular position, then the *other* combination of another 6 legs in the same position will be in a non-singular position (Fig. 1).

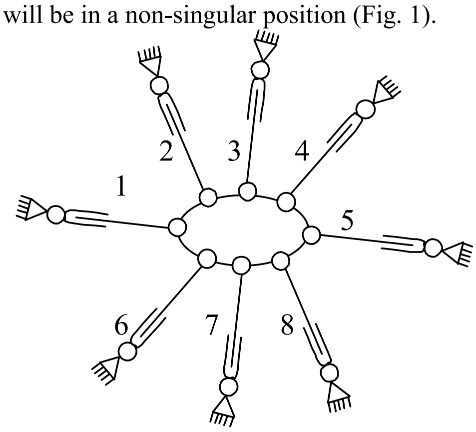



Fig. 1 The principle of redundant actuation of parallel robots

For example in plane we may use 4 legs and choose 3, in space 8 legs and choose 6 and so on for other combinations. Certainly the switching between different selected combinations of legs is just an ideal consideration. The robot must use the all redundant legs *simultaneously* and the control must be correspondingly smooth. The actuators of parallel structures can be realized by different principles, not only by telescopic links.

This principle not only removes the problems of parallel structures (especially the singularities), but it also preserves all advantages and even more. The original purpose of redundant actuation was to remove the singularities. However, there are also further advantages of redundant actuation, especially increased and more uniform dynamic capabilities, stiffness, accuracy etc. [3]. Another potential advantage of redundant parallel structures is the possibility of full on-line calibration due to redundant measurement at redundant drives.

Nevertheless from the point of view of machine control the redundant actuation of structures represents a great challenge. First, there is no unique determination of control efforts of particular drives and therefore some strategy for their unique selection may be used or is necessary. Second, there is a danger of mutual fighting of redundant drives.

## 2. Control Approach Overview

The approaches for control of redundantly actuated structures can be firstly classified according to the choice of performance criterion for the selection of redundant torques. Such performance criteria could be

- maximization of accessible acceleration (cooperation)
- maximization of accessible stiffness and/or influence on stiffness tensor (antagonism)
- removal of backlash (antagonism)
- uniform torque distribution

The cooperation control means that all the actuators are working towards the maximization of acceleration or deceleration of the parallel robot. This especially contributes to the increased dynamics. The antagonistic control means that the actuators can work against each other. Such antagonistic control actions can cause the dynamic increase of stiffness or the guarantee that the actuator torques have only one sign. It works against backlash problems of drives, thus anti-backlash control. Uniform torque distribution enables to reduce the required level of drive torques in case of redundant actuators.

Secondly, the control of redundantly actuated structures can be classified according to the level of control centralization

- decentralized control (each actuator is controlled locally)
- centralized control (control action computed on global level is decomposed into the control actions of particular actuators on local level)

and according to the distance of control horizon

- PID controller
- inverse dynamics control (IDC)
- sliding mode control (SMC)
- general predictive control (GPC)

These control approaches can provide the application of described performance criteria in the extent according to the distance of control horizon.

## 3. Antagonistic Control (Dynamic Stiffness and Anti-Backlash Control)

The parallel robot dynamics is conveniently described by Lagrange's equations of mixed type [4]

$$\begin{aligned} \mathbf{M}\ddot{\mathbf{s}} - \boldsymbol{\Phi}_s^T \boldsymbol{\lambda} &= \mathbf{g} + \mathbf{T}\mathbf{u} \\ \mathbf{f}(\mathbf{s}(t)) &= \mathbf{0} \end{aligned} \tag{1}$$

where $\mathbf{M}$ is a mass matrix, $\mathbf{s}$ is a vector of physical coordinates (their number is higher than the number of DOFs), which are constraint by kinematic constraints $\mathbf{f}(\mathbf{s}(t)) = \mathbf{0}$, $\boldsymbol{\Phi}_\mathbf{s}$ is Jacobian of these constraints, $\boldsymbol{\lambda}$ is a vector of corresponding Lagrange's multipliers, $\mathbf{g}$ is a vector of dynamic and applied forces, matrix $\mathbf{T}$ transforms the inputs $\mathbf{u}$ ($n$ torques) into $n$ drives.

The physical coordinates $\mathbf{s}$ consist of the independent coordinates $\mathbf{x}$ (conveniently Cartesian and orientation coordinates of the platform), drives' (actuators') coordinates $\boldsymbol{\varphi}$ and other auxiliary geometrical coordinates $\mathbf{q}$.

These equations of motion can be transformed into independent coordinates $\mathbf{x}$ [4] using the null space $\mathbf{R}$ of the Jacobian $\boldsymbol{\Phi}_\mathbf{s}$ which describes the relation between physical and independent coordinates $\dot{\mathbf{s}} = \mathbf{R}\dot{\mathbf{x}}$

$$\mathbf{R}^T\mathbf{M}\mathbf{R}\ddot{\mathbf{x}} + \mathbf{R}^T\mathbf{M}\dot{\mathbf{R}}\dot{\mathbf{x}} = \mathbf{R}^T\mathbf{g} + \mathbf{R}^T\mathbf{T}\mathbf{u} \tag{2}$$

Among the considered coordinates **s** there are important the coordinates of the drives **φ** and the independent coordinates of the platform **x**. There is the mapping from independent coordinates to the coordinates of drives

$$\boldsymbol{\varphi} = \boldsymbol{\varphi}(\mathbf{x}) \tag{3}$$

$$\dot{\boldsymbol{\varphi}} = \frac{d\boldsymbol{\varphi}}{d\mathbf{x}}\dot{\mathbf{x}} = \mathbf{J}\dot{\mathbf{x}} \tag{4}$$

The force interaction of the robot with the environment can be described by the forces **F** acting on the platform (they are acting on the independent coordinates **x**) and by the drive torques **n** (they are acting on the coordinates of drives **φ**). Their mutual relation is

$$\mathbf{F} = \mathbf{J}^T\mathbf{n} \tag{5}$$

The stiffness of the robot can be defined in the drive space of coordinates **φ** as

$$\mathbf{K}_{\varphi} = -\frac{d\mathbf{n}}{d\boldsymbol{\varphi}} \tag{6}$$

and in the operational space of coordinates **x** as

$$\mathbf{K}_x = -\frac{d\mathbf{F}}{d\mathbf{x}} = -\frac{d}{d\mathbf{x}}(\mathbf{J}^T\mathbf{n}) = -\frac{d\mathbf{J}^T}{d\mathbf{x}}\mathbf{n} + \mathbf{J}^T\mathbf{K}_{\varphi}\mathbf{J} = \mathbf{K}_{xa} + \mathbf{K}_{xp} \tag{7}$$

The component $\mathbf{K}_{xp}$ is called passive stiffness and the component $\mathbf{K}_{xa}$ active stiffness. In case of redundant actuators the active stiffness has interesting properties. Because in the case of redundant actuation the robot drives are not determined uniquely, thus the different choices of drive torques n which fulfill the same robot motion requirement can be used for the modification of robot stiffness [5]. Based on that different stiffness control tasks can be solved such as direction stiffness maximization, stiffness direction modifications etc. The fundamental advantage of such stiffness is that it reacts without any time delay which is the main problem of feedback control.

However, in case of redundant parallel robots the analyses have shown that this active stiffness is very small compared to the traditional stiffness of the servodrives. It is due to the fact that the redundantly actuated parallel robots have the uniform dexterity, i.e. uniform Jacobian values and the effect due to the nonlinear Jacobian properties is reduced. The more redundant actuators, the more freedom in influencing the active stiffness, however the less values of the active stiffness. This has been simulated for different robots and measured on laboratory model of redundant parallel robot Crosshead (Fig. 2).

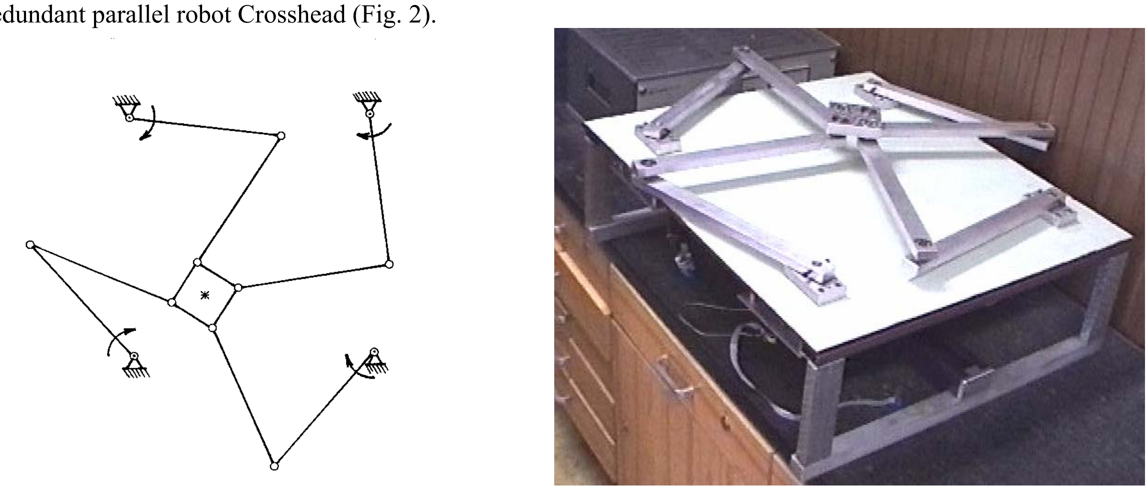


Fig. 2. Scheme and laboratory model of planar Crosshead

Another problem which can be solved by the redundant actuation is the anti-backlash control [6, 7]. The adverse influence of backlash in drives on the robot control (see Fig. 3) can be removed if the drive torques have the same sign during the whole robot motion. Let us suppose that such sign vector **S**=sign(**n**) exists. Let us modify the vector of torques and Jacobian accordingly

$$\mathbf{n}_S = \mathbf{n}\, diag(\mathbf{S}), \quad \mathbf{J}_S = \mathbf{J}\, diag(\mathbf{S}) \tag{8}$$

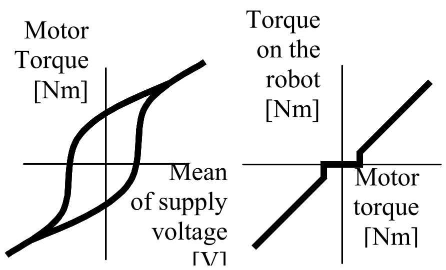
The solution condition is that for each force vector **F** there exists nonnegative solution $\mathbf{n}_S$ in certain region

$$\mathbf{J}_S^T \mathbf{n}_S = \mathbf{F} \tag{9}$$

This means that each vector in space of forces **F** can be expressed as the nonnegative linear combination of column vectors of modified Jacobian $\mathbf{J}_S^T$. This can be reduced to condition that just some positive linear combination of modified Jacobian columns creates closed polygon

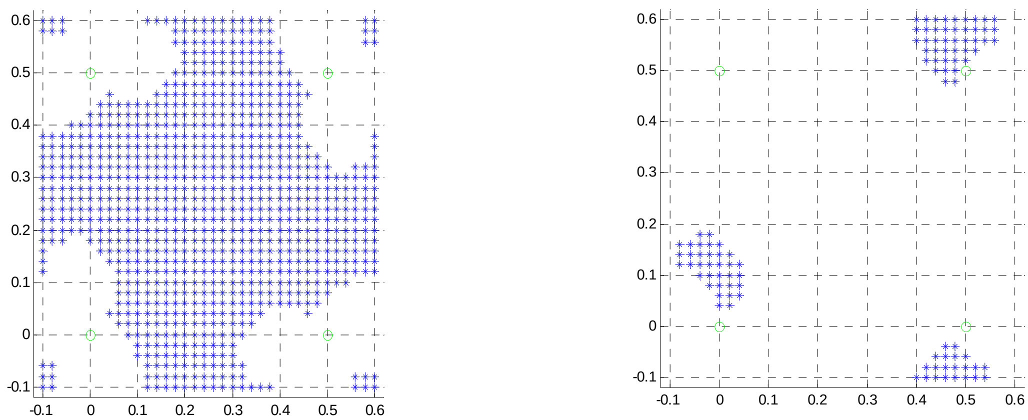
$$\begin{aligned} &\mathbf{J}_S^T \xi = 0 \\ &\xi > 0 \end{aligned} \tag{10}$$

And this problem can be solved by linear programming for each sign combination. The part of workspace of Crosshead (Fig. 2) where such antibacklash solution exists for two different sign combinations are on Fig. 4.




(a) (b)

Fig. 3 The backlash characteristics occurred in a robot:(a) the DC motor hysteresis backlash; (b) the gearing backlash.




(a) (b)

Fig. 4 Antibacklash region in Crosshead workspace for drive sign combination [1 –1 1 –1] (a) and [1 –1 1 1] (b)

## 3. Possible Control Methods for Redundant Actuation

Once the performance strategy of control of redundant actuators is selected the preplanned robot behaviour is to be controlled by some controller. There have been developed many suitable possible controllers for redundantly actuated structures. However, first let us briefly consider the danger of actuator fighting.

### 3.1 Control Problems of Redundant Actuation

If the traditional approach of cascade PID controllers on position, velocity and current level is applied there is the serious problem of mutual fighting of redundant actuators. It is due to the fact that the kinematic model of the redundant parallel structure is never perfect. Due to the redundancy of drives there is no one-to-one mapping from coordinates of drives $\boldsymbol{\varphi}$ to independent coordinates $\mathbf{x}$ (inverse of (3)). The dependence of redundant coordinates of drives on independent coordinates represents a constraint among the drive coordinates (3).

This means that the drive coordinates $\boldsymbol{\varphi}$ are dependent. This constraint is in reality not satisfied due to the imperfection of kinematic model and PID controller tries to achieve zero errors for all dependent drive coordinates $\boldsymbol{\varphi}$. It is not possible and the result is the increase of drive torques up to the saturation. Such behaviour was achieved by both simulation (Fig. 5) [8] and laboratory experiments on laboratory model of redundant parallel robot Crosshead (Fig. 2).

### 3.2 Decentralized (Local) Control

In order to solve this problem there have been developed the following modification of traditional cascade drive control. In fact it is decentralized (local) control of drives. The proposed control scheme is on Fig. 6. The only modification is the block of transformation. Its idea is that the local decentralized controllers compute the desired drive torques $\mathbf{n}_d$. From them the desired resulting forces $\mathbf{F}_d$ acting on the platform can be computed

$$\mathbf{F}_d = \mathbf{J}^T \mathbf{n}_d \tag{4}$$

Now the applied drive torques $\mathbf{n}$ are to be determined from underdetermined system of linear equations

$$\mathbf{J}^T \mathbf{n} = \mathbf{F}_d \tag{5}$$

The solution of this problem which minimizes the values of $\mathbf{n}$ is

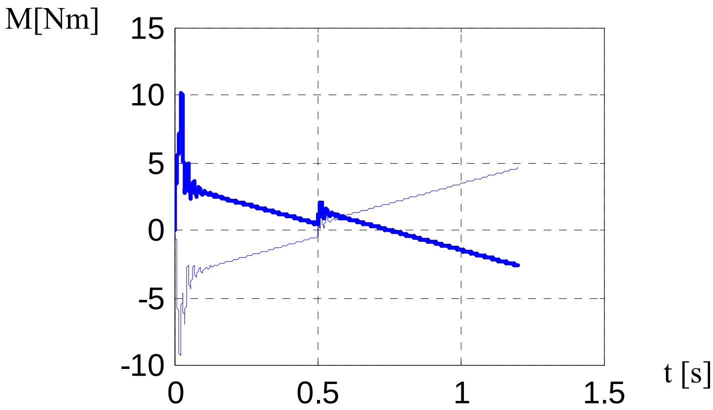



Fig. 5 Simulation of PID fighting (torque versus time)

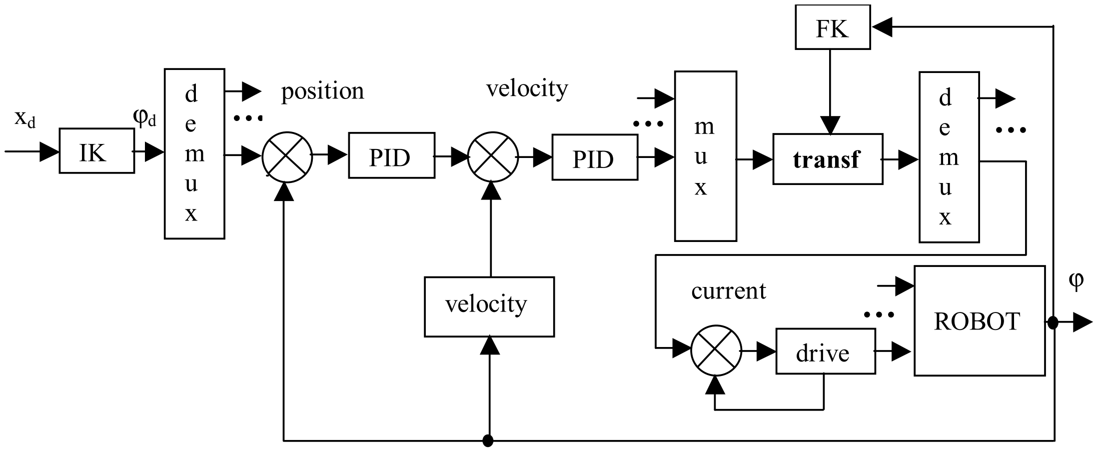



Fig. 6 Control scheme of modified decentralized control (IK=inverse kinematics, FK=forward kinematics)

$$\mathbf{n} = \mathbf{J}(\mathbf{J}^T\mathbf{J})^{-1}\mathbf{J}^T\mathbf{n}_d \tag{6}$$

The simulation of this scheme has proved that the problems of redundant drive fighting is removed. Nevertheless the scheme has been implemented in simplified form on the laboratory model of Crosshead only on the integral component of the controller (Fig. 7). The practical experiments have shown full applicability of this approach.

On Fig. 8 there is a comparison of the time histories in both ideal, geometrically accurate, case (c, d) and in real case (a, b) with geometrical inaccuracies. In the ideal situation (c) the integral/sum part levelled off at certain magnitude, which was integrated during the whole control process. In case (d) this unproductive part is reduced/ compensated to zero value. The cases (a, b) are caused by integration/sum of the lasting fictitious control error, which appears from geometrical inaccuracies in parallel construction (interaction of the actuators in close-loop systems).

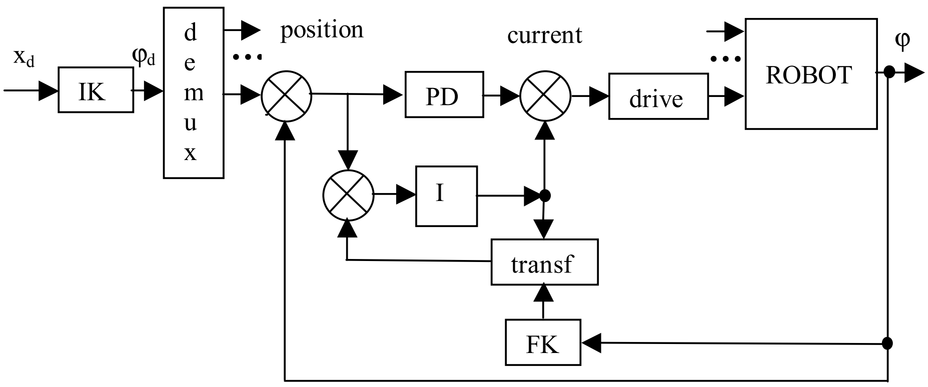



Fig. 7 Implemented control scheme of modified decentralized control

A special development was devoted for the on-line solution of forward kinematics of redundant parallel robots. The approach of differential kinematics being on-line integrated was successfully applied [9].

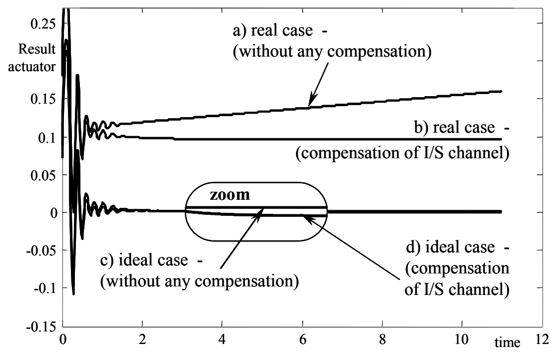



Fig. 8 Behaviour of an redundant actuator at the end of motion

### 3.3 Centralized (Global) Control

The problem of control of redundant parallel robots is the interaction among parts and redundant actuator of the robot which are not independent. The general solution of this problem is to control the robot from the centralized (global) point of view where the interactions can be directly taken into account.

The simplest control approach is to apply PID controller however on the global level [8]. The corresponding control scheme is on Fig. 9. The approach is based on the control of the independent Cartesian and orientation coordinates **x** of the platform on level of positions and velocities. The result of these blocks is a fictitious control force **F** acting directly on the platform. This force must be transformed into local drive torques **n** according to the solution of (5). Taking into account the solution with minimum values the result of the transformation from Fig. 7 is similar to (6)

$$\mathbf{n} = \mathbf{J}(\mathbf{J}^T\mathbf{J})^{-1}\mathbf{F} \tag{7}$$

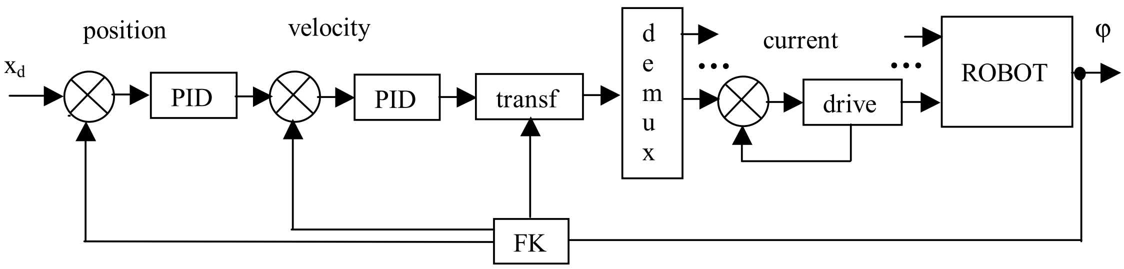



Fig. 9 Control scheme of centralized control (FK=forward kinematics)

More advanced solution is based on the knowledge of inverse dynamics [10, 11]. The equations of motion (2) are solved for independent acceleration

$$\begin{aligned}\ddot{\mathbf{x}} &= (\mathbf{R}^T\mathbf{M}\mathbf{R})^{-1}(-\mathbf{R}^T\mathbf{M}\dot{\mathbf{R}}\dot{\mathbf{x}} + \mathbf{R}^T\mathbf{g}) + (\mathbf{R}^T\mathbf{M}\mathbf{R})^{-1}\mathbf{R}^T\mathbf{T}\mathbf{u} \\ \ddot{\mathbf{x}} &= \mathbf{f}(\mathbf{x},\dot{\mathbf{x}}) + \mathbf{g}(\mathbf{x})\mathbf{u}\end{aligned} \tag{8}$$

The inverse dynamics control (IDC) is based on the idea of solution the equations (8) for the control **u**

$$\mathbf{u} = \mathbf{g}(\mathbf{x})^{-1}(\ddot{\mathbf{x}} - \mathbf{f}(\mathbf{x},\dot{\mathbf{x}})) = \mathbf{g}(\mathbf{x})^{-1}(\mathbf{q} - \mathbf{f}(\mathbf{x},\dot{\mathbf{x}})) \tag{9}$$

which results into the overall behaviour $\ddot{\mathbf{x}} = \mathbf{q}$. The suitable choice of **q**, for example as

$$\mathbf{q} = -\mathbf{K}_P\mathbf{y} - \mathbf{K}_D\dot{\mathbf{y}} + \mathbf{r} \tag{10}$$

stabilizes the system. There were assumed the inversion of the matrix **g**. This matrix is in case of redundant parallel robots a rectangular matrix. Its solution is not unique. There is necessary to apply special methods for its solution, but its solution can be used for applying the additional conditions on the robot control, e.g. antibacklash [12].

In similar way [11] the sliding mode control (SMC) can be extended from traditional robots into redundant parallel robots. Again this approach uses some knowledge about the system model. It results into the inversion of certain control effort. Within this inversion which is not unique for redundant actuation the additional conditions on the robot control can be easily raised.

The most variable control approach is generalized predictive control (GPC) [11]. The equations of motion (8) are transformed into state space description, linearized by decomposition

$$\dot{\mathbf{X}} = \mathbf{f}(\mathbf{X}) + \mathbf{g}(\mathbf{X})\mathbf{u} = \mathbf{A}(\mathbf{X})\mathbf{X} + \mathbf{g}(\mathbf{X})\mathbf{u} \tag{11}$$

and discretized

$$\begin{aligned} \mathbf{X}(k+1) &= \mathbf{A}\,\mathbf{X}(k) + \mathbf{B}\,\mathbf{u}(k) \\ \mathbf{y}(k) &= \mathbf{C}\,\mathbf{X}(k) \end{aligned} \tag{12}$$

where sense of **X** and **y** are the same as in (2). The base of predictive control is the expressing of new unknown output values **y** from actual topical state **X**. The following rows imply it.

$$\begin{aligned} \mathbf{y}(k) &= \mathbf{C}\quad \mathbf{X}(k) \\ \mathbf{X}(k+1) &= \mathbf{A}\ \ \mathbf{X}(k) + \qquad \mathbf{B}\,\mathbf{u}(k) \\ \hat{\mathbf{y}}(k+1) &= \mathbf{CA}\ \ \mathbf{X}(k) + \mathbf{C}\qquad \mathbf{B}\,\mathbf{u}(k) \\ &\ \ \vdots \qquad\qquad\qquad \vdots \\ \hat{\mathbf{X}}(k+N) &= \mathbf{A}^N\,\mathbf{X}(k) + \ \mathbf{A}^{N-1}\mathbf{B}\,\mathbf{u}(k) + \cdots + \ \mathbf{B}\,\mathbf{u}(k+N-1) \\ \hat{\mathbf{y}}(k+N) &= \mathbf{CA}^N\,\mathbf{X}(k) + \mathbf{CA}^{N-1}\mathbf{B}\,\mathbf{u}(k) + \cdots + \mathbf{CB}\,\mathbf{u}(k+N-1) \end{aligned} \tag{13}$$

prediction of **y** is then following

$$\hat{\mathbf{y}} = \mathbf{G}\,\mathbf{u} + \mathbf{f} \tag{14a}$$

$$\text{where}\quad \mathbf{G} = \begin{bmatrix} \mathbf{C} & \mathbf{B} & \cdots & 0 \\ \vdots & & \ddots & \vdots \\ \mathbf{CA}^{N-1}\mathbf{B} & & \cdots & \mathbf{CB} \end{bmatrix} \quad\text{and}\quad \mathbf{f} = \begin{bmatrix} \mathbf{CA} \\ \vdots \\ \mathbf{CA}^N \end{bmatrix} \mathbf{X}(k) \tag{14b}$$

Now we can optimize quadratic criterion at certain instant $k$ using predictions of $\mathbf{y}$ ( $\hat{\mathbf{y}} = [\hat{\mathbf{y}}_{k+1} \cdots \hat{\mathbf{y}}_{k+N}]^T$ )

$$\begin{aligned} J_k &= \mathcal{E}\ \left\{ (\hat{\mathbf{y}} - \mathbf{w})^T (\hat{\mathbf{y}} - \mathbf{w}) + \mathbf{u}^T \lambda\, \mathbf{u} \right\} = \\ &= \mathcal{E}\ \left\{ (\mathbf{G}\,\mathbf{u} + \mathbf{f} - \mathbf{w})^T (\mathbf{G}\,\mathbf{u} + \mathbf{f} - \mathbf{w}) + \mathbf{u}^T \lambda\, \mathbf{u} \right\} \end{aligned} \tag{15}$$

where $\mathcal{E}$ is operator of mean value, $N$ is horizon of prediction, **y** is vector of outputs, **w** are desired values, $\lambda$ is penalization of input and **u** is vector of robot inputs. Minimization of this performance index gives

$$\mathbf{u} = \left(\mathbf{G}^T \mathbf{G} + \lambda\right)^{-1} \mathbf{G}^T (\mathbf{w} - \mathbf{f}) \tag{16}$$

This control law is applied. It must be noted that only the first element $\mathbf{u}_k$ from vector **u** is used. If penalization $\lambda$ is greater than zero, the matrix $\mathbf{G}^T \cdot \mathbf{G}$ is regular and the problem with redundant action disappears. For additional constraint of actuators the quadratic programming is used. Again this enables to apply additional requirements on the selection of non-unique redundant controls.

The comparison of properties of all advanced centralized control approaches [11] is on Fig. 10 on example of Crosshead. It demonstrates their general properties. The closest tracking of the desired trajectory is achieved by SMC. The control by IDC is smoother as the discrepancies between modelled and real dynamics are smoothened by second order system (10). The smoothest control with greatest variety is obtained by GPC especially with multistep horizon.

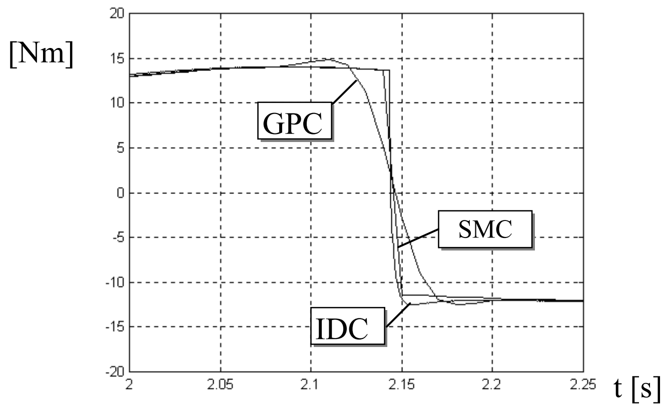



Fig. 10. Zoom of fourth drive of Crosshead for IDC, SMC, GPC control approaches

## 4. Calibration of Redundant Parallel Structures

Calibration is probably the only way how to obtain accurate kinematic model of the robot. There have been proposed two calibration techniques [13, 14]. The first one uses the fact that the platform is usually small enough to be measured by measuring machine in contrast to the frame. The calibration concerns the dimensions of the machine frame and the initial dimensions of the legs. The principle of the calibration procedure is that the platform is moved from the chosen reference position into different positions in the workspace. This relative displacement of the platform is measured and thus known. During this platform motion also the displacement of the leg actuator is measured (leg extension or leg sliding). The equations for the square of the distance between points on the frame and corresponding vertexes on the platform are substracted from the equation for the reference position. The resulting equations are linear algebraic equations for coordinates of points on the frame and the initial dimensions of the legs. The principle of these measurements are on Fig. 11 and Fig. 12. The necessary precision of these measurements can be achieved by the laser interferometer with fibre optics. Its advantage is the calibration is decomposed into the calibration of particular legs. This technique has been practically applied for calibration of laboratory model of Octapod. The simulated as well as measured results have shown that the ratio between accuracy of measurements (Fig. 11, 12) and the accuracy of calibrated dimensions is about 1:40.

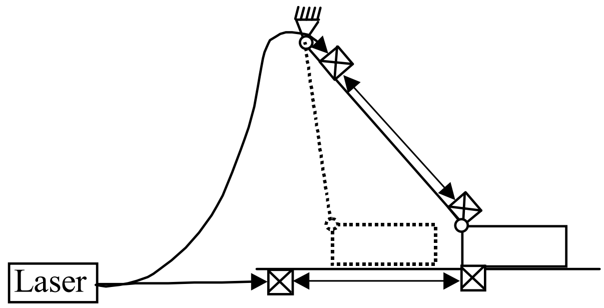



Fig. 11 Simultaneous laser measurements of platform and extensible leg actuator motion

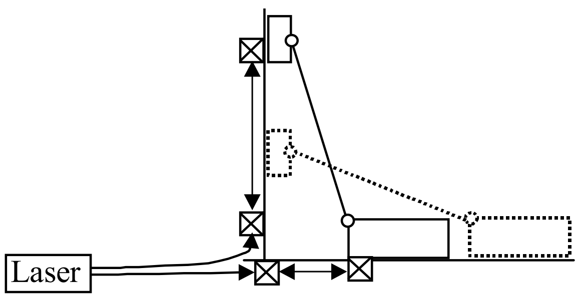



Fig. 12 Simultaneous laser measurements of platform and sliding leg actuator motion

The second calibration technique uses the unique advantage of redundant parallel robots. If all drives are equipped with measurement of drive displacement then during each motion of redundant parallel robot there is redundant number of measurements. The assembled equations of constraints for certain number of robot positions can be solved for both robot dimensions and initial positions. These equations are nonlinear ones. This approach has the great advantage that the redundant parallel robots can be calibrated on-line during their operations without using any external equipment or breaking their work. This approach has been simulated for many robots and results for Octapod have shown that the ratio between accuracy of measurements of drive displacements and the accuracy of calibrated dimensions is about 1:60.

## 5. Conclusions

The redundant actuation of parallel robots enables to remove their serious disadvantages and to bring many advantages. However, their control and calibration represent challenges. There have been developed several techniques which solve these challenges. Finally it means that the concept of redundant parallel robots is ready for practical applications.

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