Master Device For Micro Tele-Operation Systems

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Abstract

This paper describes a micro tele-operation system, which enables human operators to operate micro tasks, such as assembly or manufacturing, without feeling stress. The paper focuses on the haptic interface, which gives the operators the feeling of presence. The mechanism applied in the human interface device has a reasonable immanent friction usually. This friction must be compensated in a way that the operator cannot feel this friction force but only the force from the manipulated environment. The main contribution of this paper is a direct model based chattering free sliding mode friction estimator and compensator for a human interface device. Experimental results are presented.

1. INTRODUCTION

In recent years, mobile phone, personal electrical devices, including mobile PC, PDA, etc. are becoming smaller and smaller. Concurrently, the electronic parts and components are also becoming smaller and smaller. On the other hand, human operator are still required to manipulate such small parts. Such as, mechanical lenses driver alignment in MD/CD player, small print pattern repair work are typical examples. The reason is the human operators flexibility difficult to be developed, taught or achieved in robotics systems. This flexibility allows the human to handle with electronics parts specification modification. However, stressfull environment is the biggest problem, which operator feel in these kinds of tasks. The stress is caused by the scale differences between human and manipulated objects. In our research, we consider the micro-manipulation as one of the teleoperation and the parallel manipulator applications. In this case, the teleoperation should connect the micro-workspace with the human workspace. It will solve the scale difference problem between the human operator and micro objects. The system aims to provide a more comfortable environment for task execution and work efficiency improvement.

The structure of this paper as follows. The next section introduces the basic structure of the micro teleoeration system.. Section 3 introduces the theory of disturbance compensation, which is used for friction compensation in a way that the operator cannot feel this friction force but only the force from the manipulated environment. Section 4 presents experimental results for the 6 degree of freedom micro tele-operation system and session 4 draws the conclusion of this paper.

2. SYSTEM COMPOSITION

A micro teleoperation system shown in Fig.1 was developed. Not only visual interfaces was introduced but also original haptic interfaces which feedback force and offer the presence to operetors.

2.1 Slave device

As a slave device, a parallel link manipulator[1,2] was developed, which has 6 degrees of freedom. In general, parallel link structure has good features of precision and stiffness, although it has small workspace and many singular points [3]. This structure was adopted because its characteristic is proper for precise works. It has 3 degrees of freedom for XYZ linear motion and 3 degrees of freedom for rotation of each axis. Its workspace is almost 30mmX30mmX30mm for linear motion and +/- 15 degrees for rotation. Different from general Stewart Platform, it has novel structure: Six links which sprouted verticality from base table can expand and contract. Each two links of six links are combined into one by sublink. Ultimately, the end effector table is holded by total 3 points. The structure is shown on Fig.2. This manipulator is controlled by a PC (dual Pentium III 500MHz). Operating System is Real Time Linux (RT-Linux) in order to perform motor control with 2.5kHz sampling time. Input-output using motor, rotary encoder, force sensor are performed by AD, DA, counter, DIO boards connected to an extended bus. As actuators, six AC servomotor of the same type are installed, and 1mm pitch ball screws are connected to each motor.

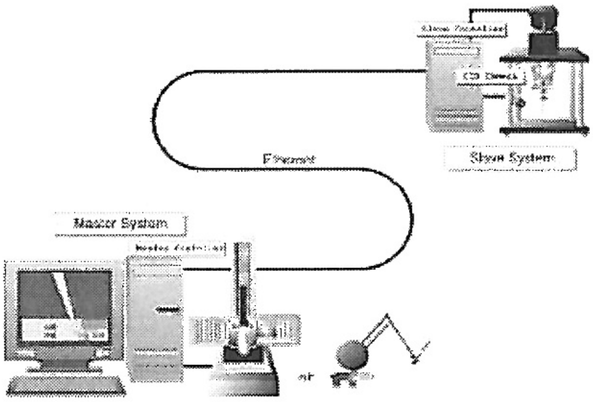


Fig. 1. Overview of the Micro Tele-Operation System

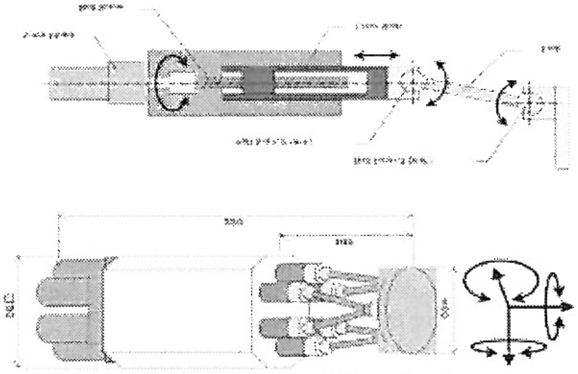


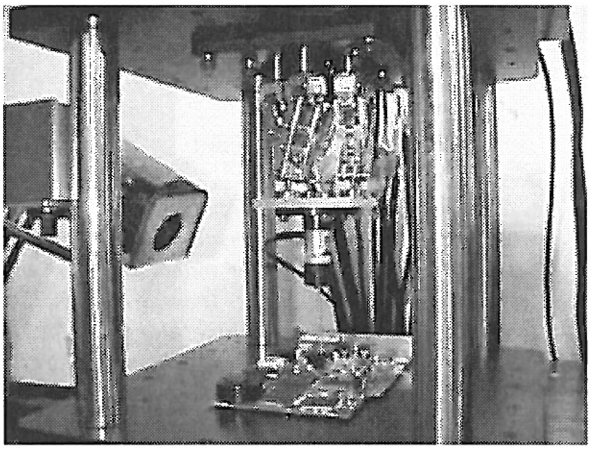
Fig.2. Structure of Slave Device

By adopting this structure, we can save space although analysis of kinematics and dynamics becomes difficult. Workspace and singular points, peculiar to this structure, need to be analyzed. The appearance of the slave device is shown in Fig.3.

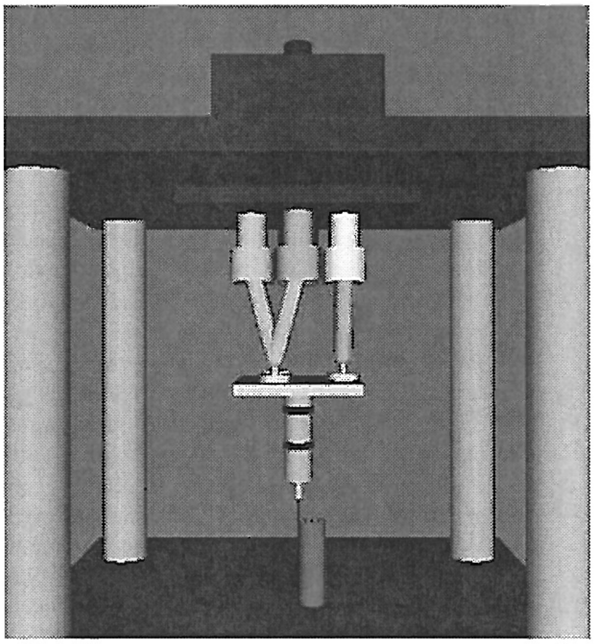
2.2 Master device

The structure of master device is wished to be same as the slave device. However since parallel link structure has small workspace, if it is adapted to human scale, whole facilities become very big. Thus we adopted serial link structure to get large workspace, although it decreases accuracy and stiffness. Our master device is stick-type device composed of 3 linear servo motors which realize 3 axis (X, Y, Z) parallel movement and 3 AC servo motors which realize rotation around each axis (φ, θ, ψ). It covers all 6 degrees of freedom of the slave device. The holds the master-stick in his hand and he can move and rotate it.

By adopting this structure, it realizes large workspace (linear movement: 340mmx340mmx340mm, rotation +/1 15 degrees for each axis). It has the ability of force feedback to all degrees of freedom. The appearance and the structure of the master device are shown in Fig.4 and Fig. 5. PC and I/O system configuration is shown in Fig. 6.



a. Photo



b. Animation

Fig.3. The appearance of the Slave Device

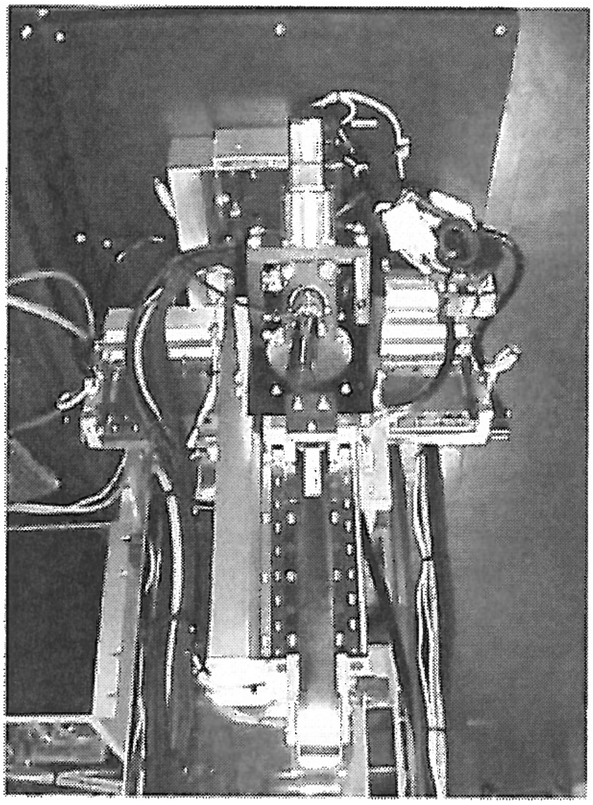


Fig. 4 The appearance of the Master Device

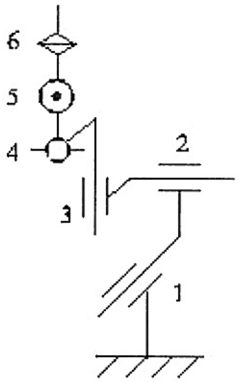


Fig.5. Structure of Master Device

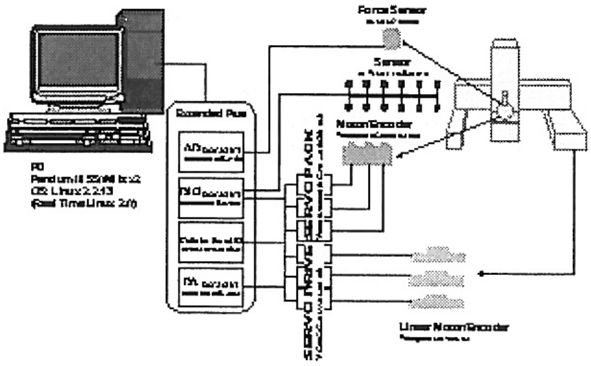


Fig.6. System setup of Master Device

3. SLIDING MODE BASED DISTURBANCE OBSERVER

Consider the following model with external disturbances and uncertain parameters satisfying the so-called Drazenovic condition [4], written in the regular state equation form,

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} \overline{A}_{11} & \overline{A}_{12} \\ \overline{A}_{21} + \Delta A_{21} & \overline{A}_{22} + \Delta A_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \overline{B}_2 + \Delta B_2 \end{bmatrix} u^0 + \begin{bmatrix} 0 \\ E_2 \end{bmatrix} f(t) \tag{3}$$

where $x_1 \in R^{n-m}, x_2 \in R^m, u \in R^m, \overline{A}_{ij}(i,j=1,2)$ and $\overline{B}_2$ denote the nominal or desired (ideal) system matrices. The bar $\overline{\bullet}$ refers to the reference value in this paper. $\Delta A_{2j}(j=1,2)$ and ΔB_2 are the respective uncertain perturbations and f(t) is an unknown, but bounded disturbance with bounded first time derivative with respect to time.

Now η is defined as the uncertainties and the disturbance of the system.

$$\eta = \Delta\overline{A}_{21}x_1 + \Delta\overline{A}_{22}x_2 + \Delta\overline{B}_2u^0 + E_2f(t) \tag{4}$$

The second line of (3) can be rewritten by η.

$$\dot{x}_2 = \overline{A}_{21}x_1 + \overline{A}_{22}x_2 + \overline{B}_2u^0 + \eta \tag{5}$$

According to [5], $\hat{x}_2$ is estimated by a discontinuous observer:

$$\dot{\hat{x}}_2 = \overline{A}_{21}x_1 + \overline{A}_{22}\hat{x}_2 + \overline{B}_2\left(u^0 + v\right) \tag{6}$$

where v is the discontinuous feedback. The goal of the design to find a feedback signal, denoted v, such that the motion of the system (3) is restricted to belong the manifold S.

$$S = \left\{x_2 \middle| \sigma = x_2 - \hat{x}_2 = 0\right\} \quad \text{where } \sigma \in R^m. \tag{7}$$

The simplest control law, which can lead to sliding mode, is the relay:

$$v_i = M_i \operatorname{sign}\left(\sigma_i\right) \tag{8}$$

If η is in the range of B_2 ($\eta \subset$ range (B_2)), the ideal sliding mode occurs [6].

If the system trajectory is on the sliding surface then there is a continuous control signal, so called equivalent control signal, v_{eq}, which can hold the system on the sliding manifold, (but it does not guarantee the convergence to the sliding manifold in general). If the system is in sliding mode ($\sigma = 0$ and $\dot{\sigma} = 0$),

$$\dot{\sigma} = \underbrace{\Delta A_{21}x_1 + \Delta A_{22}x_2 + \Delta B_2u^0 + E_2f}_{\eta} - \overline{B}_2v_{eq} \tag{9}$$

$$\overline{B}_2 v_{eq} = \Delta A_{21} x_1 + \Delta A_{22} x_2 + \Delta B_2 u^0 + E_2 f = \eta . \quad (10)$$

Clearly, v_{eq} contains information on the system's parametric uncertainties and the external disturbance, which can be used for feedback compensation.

Supposing for the time being that v_{eq} is known and a modified control input signal is used.

$$u^0 = u - v_{eq} \quad (11)$$

According to (5) and (10), the system response for (11) coincides with the nominal or ideal, undisturbed system response for the control u,

$$\dot{x}_2 = \overline{A}_{21} x_1 + \overline{A}_{22} x_2 + \overline{B}_2 u \underbrace{- \overline{B}_2 v_{eq} + \eta}_{0} \quad (12)$$

In the practice, there is no way to calculate the equivalent control v_{eq} precisely, but it can be estimated by a low pass filter for v as showed in Fig. 7. In [7] an additional control parameter introduced, instead of low pass filter. There are two loops on Fig. 7. The observer – sliding mode controller loop should be as fast as possible to achieve an ideal sliding mode. This is granted because this loop is realized in a computation engine in the recent application. The real system – compensator (consisting of Sliding Mode Controller and LPF) loop should be faster than the change of the disturbance. On the other hand, the smallest unmodeled resonant frequency of real system should be out of the bandwith of that loop to avoid chattering.

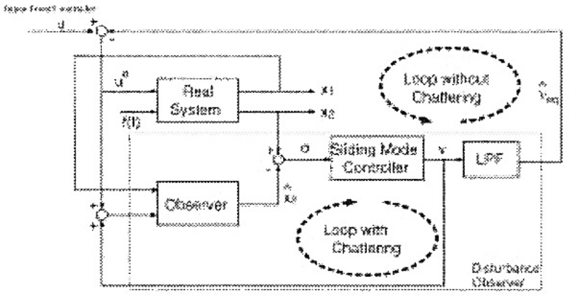


Fig. 7. Sliding mode based feedback compensation

3.1 Chattering free implemen-tation of sliding mode

The robustness of continuous time sliding mode control is realized by the high-frequency switching of the discontinuous observer feedback signal v. To adapt the sliding mode philosophy for a discrete time observer [7], the sampling frequency should be increased compared to Lumberger observer. If the switching frequency of the relay (8) is not enough high, σ might chatter around the manifold $\sigma = 0$ as shown on Fig. 8, where T^k denotes the time of k-th sampling. In case of discrete-time observer, the observer feedback signal v may switch from $+M_i$ and $-M_i$ and vice versa resulting $v^k_{eq} = 0$ even if $v_{eq} \neq 0$. The bigger the M_i is, the bigger the chattering is. In the other hand, if M_i is smaller than the disturbances, it cannot eliminate it.

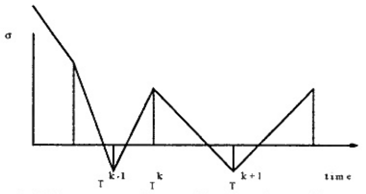


Fig. 8. Discrete-time chattering phenomenon

Applying the Lyapunov stability theory, let the positive definite Lyaponov function candidate is chosen in the following form:

$$V = \sigma^T \frac{\sigma}{2} \quad (13)$$

The observer feedback is chosen in such a way, that the derivation of the Lyaponov function meet the following condition:

$$\dot{V} = \sigma^T \dot{\sigma} < 0, \quad (14)$$

As it was proposed in [7,8], the condition (14) is satisfied if

$$\dot{V} = -\sigma^T D \sigma \quad \text{in other words}: \dot{\sigma} = -D\sigma \quad (15)$$

where D is a positive definite matrix. According to (5), (6) and (7)

$$\dot{\sigma} = \overline{A}_{22} \underbrace{\left(x_2 - \hat{x}_2 \right)}_{\sigma} - \overline{B}_2 \left(v + \eta \right) \quad (16)$$

Applying (10), the equivalent observer feedback can be expressed from (16)

$$v_{eq} = v + \overline{B}_2^{-1} (\dot{\sigma} - \overline{A}_{22} \sigma) \quad (17)$$

To meet the condition (15), the observer feedback is chosen in the following way

$$v = \overline{B}_2^{-1} \sigma (D + \overline{A}_{22}) + v_{eq} \quad (18)$$

The first term is responsible for the chattering free reaching of the sliding manifold, but it is 0, if the system in sliding mode. Since v_{eq} is not known, it must be estimated. Supposing, that the equivalent observer feedback is changing smoothly, (17) is estimated at the k-th sampling period by

$$\hat{v}^k_{eq} = v^{k-1} + \overline{B}_2^{-1} ((\sigma^k - \sigma^{k-1}) / T - \overline{A}_{22} \sigma^k) \quad (19)$$

where T is the sampling period. Substituting (19) in the discrete form of (18)

$$v^k = v^{k-1} + (\overline{B}_2^{'})^{-1} \left(D' \sigma^k - \sigma^{k-1} \right) \quad (18)$$

where $\overline{B}_2^{'} = \overline{B}_2 T$, and D'=TD+I.

4. EXPERIMENTAL RESULTS: DESIGN OF FRICTION COMPENSATION FOR A SINGLE JOINT

The method described in Section 3 was applied for a single joint. From the point of view of the operator the whole dynamics of the mechanism (not only the friction) is disturbance. The whole dynamics of the system cannot be eliminated (since it would needed infinite input power) but the effect of the friction can be compensated. The aim of the compensation is to make the system follow an ideal model with small friction and with small dynamics. In other words, because of the compensation, the operator feels that it is very easy to move the master-stick. From now on, the nominal model of the motor is used as an ideal model of the system, which includes gear, belt and other mechanism.

4.1 Position control

The control parameters were tuned and the effect of friction compensation was verified by a position control experiment. The control scheme is shown in Fig. 9.

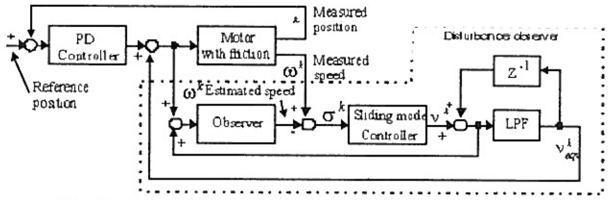


Fig.9. Overall control scheme for position control

In order to emphasize the compensation capability of the method a simple PD controller is tested, which cannot eliminate the effect of the friction itself. So this measurement can be used for tuning the parameters of sliding mode compensator. The reference signal is a step change of 100 mm, as shown in Fig. 10.

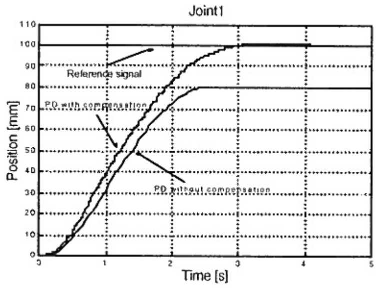


Fig. 10. Position control measurement

Fig. 10. shows the time functions of the reference and the measured positions. It is well known, that the *PD* controller can not eliminate the steady state error (see Fig. 10). The master-stick is sticked at 80% of the reference value. The same *PD* controller with compensation using disturbance observer can eliminate this error. These results demonstrate the effectiveness of the sliding mode based disturbance observer.

4.2 Free motion of master-device

The overall control system for free motion of one degree of freedom is shown in Fig. 11. The input signal of the PID controller is zero, which means the master-sick follows the human hand.

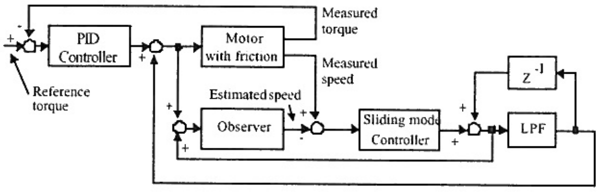


Fig.11. Overall control scheme for force control

The friction of the device should be eliminated by control. Only two degree of freedom used in this experiment. The operator moved his hand in the X-Y plane. Two controllers were compared namely a PID controller and a PID controller with disturbance compensation. The results are shown in Fig. 12 and 13.

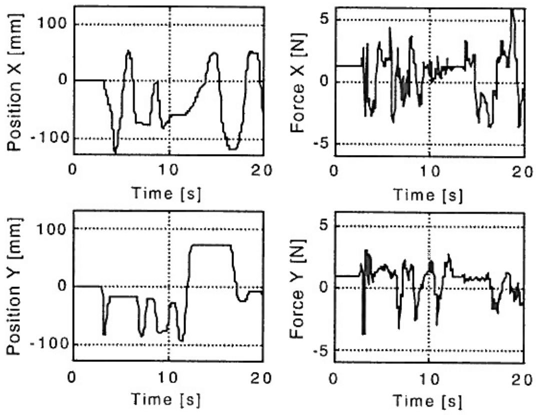


Fig.12 Friction compensation by PID controller

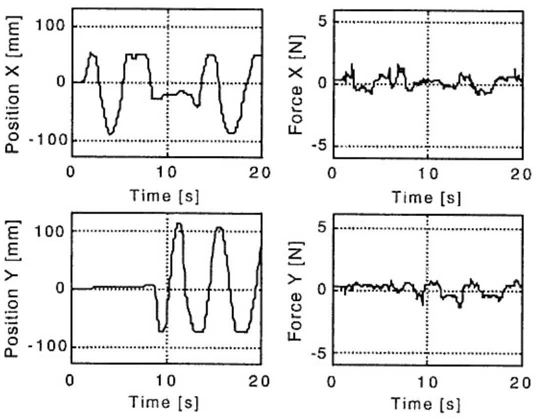


Fig.13 Friction compensation by SM observer

5. CONCLUSION

The main disturbance of a master device is the friction. In this paper, an observer based on the sliding mode is used to eliminate the friction. The nonlinear disturbance force (caused by the friction of the device) can be significantly reduced by a nonlinear sliding mode observer. The proposed method is very effective. It is supposed that the method is easy to apply to other systems satisfying the so-called matching condition [5].

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REFERENCES

[1] Kevin Cleary, Tatsuo Arai : ``A Prototype Parallel Manipulator: Kinematics, Construction, Software, Workspace Results, and Singularity Analysis," Proceedings of the IEEE International Conference on Robotics and Automation, Vol.1, pp566-571, 1991.

[2] E.F.Fichter : ``A Stewart Platform-Based Manipulator: General Theory and Practical Construction," The International Journal of Robotics Reseach, Vol.5, No.2, pp157-182, 1986.

[3] K.Fujimoto, S.Tadokoro, T.Takamori : ``Development of a 6D.O.F Direct-Drive Wrist Joint by Pneumatic Linear Actuator Drive," Proceedings of 16th Annual Conferece of IEEE Industrial Electronics Society (IECON'90), Vol.1, pp427-432, 1990.

[4] B. Drazenovic: The Invariance Condition in Variable Structure Systems, Automatica, Vol.5, No.3, pp.287-295, 1969.

[5] P. Korondi, K-K. D. Young and H. Hashimoto: Discrete-time Sliding Mode Based Feedback Compensation for Motion Control, Proc. of the 1996 IEEE Intl. Workshop on Variable Structure Systems, December 5-6, 1996, Tokyo, Japan.

[6] V. I. Utkin: Sliding Modes in Control and Optimization, Spinger–Verlag, 1992

[7] O. S. Bogosyan, M. Gokasan, A. Sabanovic: A Sliding Mode based Disturbance Observer for Motion Control Systems, VSS'99 Conference, Florida, 1999.

[8] Sabanovic A., N. Sabanovic. K. Jezernik, K. Wada, "Chattering Free Sliding Modes" The Third Worksop on Variable Structure Systems and Lyaponov Design Napoly, Italy, 1994.