시변 스위칭 평면을 이용한 로보트 매니퓰레이터의 견실한 제어기의 설계

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A Robust Controller Design for Manipulators using Time-Varying Sliding Manifolds

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Abstract

A new control algorithm is developed to achieve the robust performance of the system during the overall control process. Time-varying sliding manifolds are proposed to remove the reaching phase which is one of common shortcomings of variable structure control scheme. A necessary and sufficient condition for the existence of a sliding mode on the newly proposed time-varying sliding manifolds is derived by Lyapunov's second method. The digital simulation results show that the newly proposed control algorithm is superior to the typical variable structure control algorithm with respect to the robust performance of the system. The simplicity of the proposed control algorithm encourages control engineers to implement the proposed control algorithm in many control problems.

1. Introduction

Most of computer-controlled robots used in the world are serial linkage manipulators because their available working space is large. Such a multi-joint robot arm, however, is a highly - coupled nonlinear system with complicated interactions between each joint. As to such a complicated dynamics, quite a number of papers have presented on the aspect of manipulator control which are various control conceptions.[1]-[3]

In the conventional controller design for robotic manipulator, the control algorithm is based on nonlinear compensations of the plant. This approach requires a detailed model of the manipulator and an exact load forcast.[4] In addition, such nonlinear compensations are complex and costly to implement. In order to avoid this difficulty, several control algorithms using the theory of variable structure systems (VSS) have been developed.[5][6]

The VSS is designed in such a way that all trajectories in the state-space are directed toward some sliding manifolds. Once the system state reaches the sliding manifolds, it slides along them and the system response depends thereafter only on the gradients of the sliding manifolds and remains insensitive to a class of disturbances and parameter variations.[7]

However, there is a reaching phase in which the trajectories starting from a given initial state off the sliding manifolds tend towards the sliding manifolds. Thus, the trajectories in this phase are sensitive to a class of disturbances and parameter variations.[8]

To get around this difficulty mentioned above, we introduce the time-varying sliding manifolds which are defined from given initial states. These time-varying sliding manifolds approach the fixed original sliding manifolds within a finite time. The existence of sliding modes on these time-varying sliding manifolds are verified by Lyapunov second method.

The effectiveness of the newly proposed time-varying sliding manifolds is demonstrated through the digital simulations to 2-joint manipulator for the set-point regulations.

2. Fundermental theories of VSS with time-invariant sliding manifolds

The control algorithm presented here is derived for the set-point regulation problem and is appliable to the class of second-order dynamic equations with a positive-definite symmetric inertia matrix. .

2.1. Manipulator model

The dynamics of manipulator with n degree of freedom are generally described by the following Lagrange-Euler formulation:

$$M(q)\ddot{q} + B(q,\dot{q})\dot{q} + G(q) = U \tag{2.1}$$

where $q_d \in R^{n\times1}$ is a vector of n joint shaft angular displacements, $U\in R^{n\times1}$ is a vector of n control input torques, $M(q)\in R^{n\times n}$ is the effective moment of inertia matrix, $G(q)\in R^{n\times1}$ represents the gravitational torques and $B(q,\dot{q})\in R^{n\times n}$ denotes the Coriolis and centrifugal torques.

Let q_d represent the desired position and define a new state vector $X=(e,w)^T$ where $e(t) = q(t) - q_d(t)$ and $w(t) = \dot{q}(t)$. Then (2.1) is transformed as the following state equations:

$$\dot{X} = f(X) + g(X)U \tag{2.2}$$

where

$$f(X) = \begin{bmatrix} w \\ -M^{-1}(e+q_d)[\ B(e+q_d,w)+G(e+q_d) \end{bmatrix}$$
$$g(X) = \begin{bmatrix} 0 \\ M^{-1} \end{bmatrix} \tag{2.3}$$

Note that f,g are smooth, local vector fields defined on Σ with $g(x)\neq 0, \forall X \in \Sigma$.

2.2 Definition of a sliding mode

Let S^o denote a smooth function $S^o: \Sigma \rightarrow R$, with nonzero gradient on Σ. The set

$$S^o = \{ X \in R^n ;\ S^o(X) = CX = 0 \} \tag{2.4}$$

defines a (n-1)-dimensional submanifold in Σ and is called the sliding manifold or switching surface. The function S^o will often be addressed as the surface coordinate function.

A variable structure control law is obtained by letting the control function u_i take one of two feedback values according to the sign of $s_{io}(X)$, as defined by

$$u_i = \begin{cases} u_i^+(X) & \text{for } \overset{o}{s}_i(X) > 0 \\ u_i^-(X) & \text{for } \overset{o}{s}_i(X) > 0 \end{cases} \tag{2.5}$$

$$u_i^+ \neq u_i^- \qquad i = 1,2,\dots,n$$

Let $L_h\sigma$ denote the directional derivative of the scalar function σ with respect to the vector field h.[9] Suppose that as a result of the control policy (2.5) the state trajectories of (2.2) locally reach the sliding surface s_{io} and, from there on, their motion is constrained to the immediate vicinity of s_{io}. We say that sliding mode locally exists on s_{io} if, with u_i and u_j ($i \neq j$) given by (2.5), the following inequalities are satisfied:

$$\lim_{\overset{o}{s}_i \to 0+} L_{f+gu}\overset{o}{s}_i < 0 , \quad \lim_{\overset{o}{s}_i \to 0-} L_{f+gu}\overset{o}{s}_i > 0 \tag{2.6}$$

i.e. the rate of change of the scalar surface coordinate function $s_{io}(X)$, measured in the direction of the controlled field, is such that a crossing of the surface is guranteed, from each side of the surface, by use of the switching policy (2.5).

Let ds_{io} denote the gradient of s_{io} and let $\langle\ ,\ \rangle$ denote the standard scalar product of vectors. Then condition (2.6) are equivalent to

$$\lim_{\overset{o}{s}_i \to 0+} \langle d\overset{o}{s}_i ,\ f + gU \rangle < 0 , \quad \lim_{\overset{o}{s}_i \to 0-} \langle d\overset{o}{s}_i ,\ f + gU \rangle > 0 \tag{2.7}$$

which alternatively explains that on s_{io} the projection of the controlled vector fields $f + gU^+$ and $f + gU^-$ on the gradient vector to s_i^o are opposite in sign and hence the controlled fields locally point towards the surface s_i^o. Fig.1 shows sliding mode on a sliding manifold.

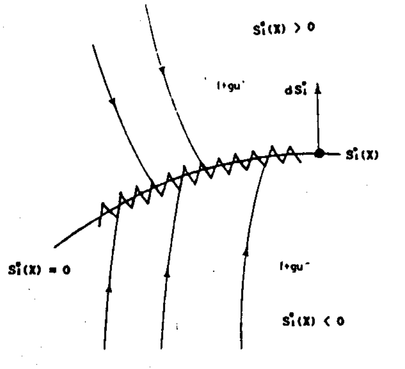

Fig.1 Sliding mode on a sliding manifold.

2.3 Ideal sliding mode dynamics.

A definition of the ideal sliding mode has been given by Utkin.[10] This definition is known as the method of equivalent control. In this approach, ideal sliding modes are described by the manifold invariance conditions:

$$\begin{aligned} &\overset{o}{s}_i(X) = 0 \\ &L_{f+gU_{eq}}\ \overset{o}{s}_i(X) = [\ \partial s_i/\partial X\ ](\ f + gU_{eq}\ ) = 0 \end{aligned} \tag{2.8a}$$

or, more briefly

$$S^o = 0, \quad [\ \partial S^o/\partial X\ ](\ f + gU_{eq}\ ) = 0 \tag{2.8b}$$

From the definition of directional derivative and (2.8) the equivalent control is explicitly given by

$$U_{eq}(X) = - \left[\frac{\partial S^o}{\partial X} g \right]^{-1} \frac{\partial S^{-1}}{\partial X} f \tag{2.9}$$

Substituting (2.9) into (2.2) yields

$$\dot{X} = \left[I - g\left[\frac{\partial S^o}{\partial X} g \right]^{-1} \frac{\partial S^o}{\partial X} \right] f \tag{2.10}$$

Equation (2.10) represents an idealized version of the motions occuring about the sliding manifolds S^o and they constitute an 'average' description for the behavior of the controlled trajectories of (2.2) and (2.5) on the sliding manifold S^o.

3. Newly proposed VSS with time-varying sliding manifolds

3.1 Newly proposed time-varying sliding manifolds

Due to the control policy (2.5) the trajectories of (2.2) starting from given initial states off the sliding manifolds tend towards the sliding manifolds. Therefore, finite time is required for the trajectories to arrive at the sliding manifolds. This finite time is called 'reaching phase'. During this period the sliding modes cannot be obtained and as a result we cannot obtain the robust performance of the system.

In this section, as an approach to remove the reaching phase, we introduce time-varying sliding manifolds on which the sliding modes occur during the overall control process. The newly proposed time-varying sliding manifolds are described as follows.

$$S(X,t) = S^o(X) + P \begin{bmatrix} t - t_{m1} \\ t - t_{m2} \\ \vdots \\ t - t_{mn} \end{bmatrix} \tag{3.1}$$

where $S^o(X) = CX$, $P = \mathrm{diag}(\ p_1\ p_2\ \dots\ p_n\ )$ and p_i is determined such that the initial trajectories of (2.2) lie on the time-varying sliding manifold $S(X,t)$:

$$p_i = \frac{\overset{o}{s}_i(X(t_o))}{t_{mi} - t_o} \qquad i = 1,2\ \dots,n \tag{3.2}$$

From above definition we can know that the proposed sliding manifolds pass through given initial states at initial time and approach the fixed original sliding manifolds $s_{io}(X)=0$.

Let d_i define as metric functions which represent the distances between $s_{io}(X)=0$ and $s_i(X,t)=0$.

$$d_i(\overset{o}{s_i}, s_i) = \frac{|\, s_{io}(X(t)) \,|}{[\, \sum_{j=1}^{n} c_{ij}^2 \,]^{1/2}} \qquad i = 1,2,\dots,n \quad (3.3)$$

where c_{ij} is (i,j)-component of the matrix C.

3.2 Selection machanism of sliding manifolds

The proposed time-varying sliding manifolds approach the fixed original sliding manifolds and pass through them when $t = t_{mi}$. To cope with this difficulty the following selection mechanism of the sliding manifolds must be adopted according to the value of $d_i(s_{io}, s_i)$.

$$s_i(X,t) = \begin{cases} \overset{o}{s_i}(X) + p_i(\, t - t_{mi}) & \text{if } d_i > \varepsilon_i \\ \overset{o}{s_i}(X) & \text{if } d_i \le \varepsilon_i \end{cases} \qquad (3.4)$$

$$i = 1\ 2,\dots,n$$

where ε_i is design factor which is selected arbitrarily at designer's disposal. But ε_i must be selected properly in view of practical situations.

Fig.2 show the newly proposed time-varying sliding manifolds and Fig.3 the selection mechanism of sliding manifolds.

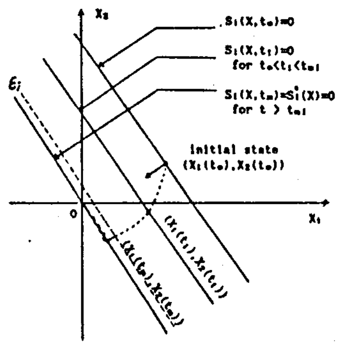

Fig.2 The proposed time-varying sliding manifolds

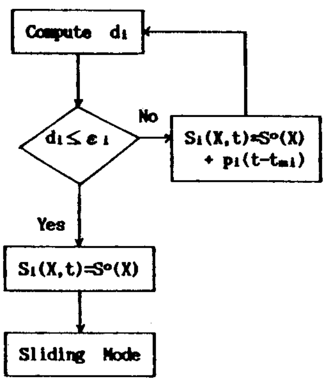

Fig.3 The selection mechanism of sliding manifolds.

3.3 Controller design using the theory of VSS

Among several control algorithm using the theory of VSS, there still exist some nontrivial difficulties in the design. A major difficulty is related to the cross-coupling in the inertia matrix.

To get around this difficulty, we introduce Chen's control algorithm[13] which takes advantage of an important property of the inertia matrix, namely its symmetric positive definiteness.[11]

3.3.1 The reachability of the time-varying sliding manifolds

Let q_d represent the desired position and choose the sliding manifolds $S^T = [\, s_1\ s_2\ \dots\ s_n \,] = 0$ as follows:

$$S = S^o + P \begin{bmatrix} t - t_{m1} \\ \vdots \\ t - t_{mn} \end{bmatrix} \qquad (3.5)$$

where

$$S^o = C^{\#}(\, q - q_d \,) + \dot{q} = [\, C^{\#} : I \,]X$$

$$C^{\#} = \mathrm{diag}[\, c_1\ c_2\ \dots\ c_n \,], \quad c_i > 0$$

$$P = \mathrm{diag}[\, p_1\ p_2\ \dots\ p_n \,], \quad p_i = \frac{\overset{o}{s_i}(X(t_o))}{t_{mi} - t_o}$$

$$i = 1,2,\dots,n$$

The design parameters c_i determine the rate of response of the system, and the aim of the control is to force the motion of the system (2.2) to be along the intersection of the sliding manifolds $S^o = 0$.

Differentiating (3.5) with respect to time yields

$$\dot{S} = C^{\#}\dot{q} + \ddot{q} + P \qquad (3.6)$$

Multiplying the matrix M to (3.6) and inserting (2.2) yields

$$M\dot{S} = MC^{\#}\dot{q} + M\ddot{q} + MP$$

$$= MC^{\#}\dot{q} - B\dot{q} - G + U + MP$$

$$= Q\dot{q} - G + MP + U \qquad (3.7)$$

where $Q = MC^{\#} - B$.

We now derive a reachability condition for the time-varying sliding manifolds using the stability theorem of Lyapunov. First assume the form of $M\dot{S}$ to be

$$M\dot{S} = -\,\Gamma \mathrm{sgn}(S) = -\,\Gamma_s S \qquad (3.8)$$

where

$$\Gamma = \mathrm{diag}\,(\, \gamma_1\ \gamma_2\ \dots\ \gamma_n \,), \quad \gamma_i > 0$$

$$\Gamma_s = \mathrm{diag}[\, \gamma_1 \mathrm{sgn}(s_1)/s_1 \,] \quad i = 1,2,\dots,n$$

$$\mathrm{sgn}^T(S) = [\, \mathrm{sgn}(s_1)\ \mathrm{sgn}(s_2)\ \dots\ \mathrm{sgn}(s_n) \,]$$

In order to prove that the sliding manifolds S=0 are asympotically stable we introduce the candidate for Lyapunov function

$$V = S^T M(q,\dot{q})S \qquad (3.9)$$

Differentiating V with respect to time and using the symmetry of M yields

$$\dot{V} = \dot{S}^T MS + S^T\dot{M}S + S^T M\dot{S}$$

$$= (M\dot{S})^T S + S^T\dot{M}S + S^T(M\dot{S}) \qquad (3.10)$$

Substituting (3.8) into (3.10) and noting that Γ_s is also symmetric gives

$$\dot{V} = -2S^T(\Gamma_s - \dot{M}/2)S \tag{3.11}$$

If ($\Gamma_s - \dot{M}/2$) can be made a positive-definite matrix, then $\dot{V}$ will be a negative-semidefinite function which vanishes only at S=0. Therefore, by means of Lyapunov's stability theory the sliding manifolds are asymptotically stable. Note that to ensure the negative definiteness of $\dot{V}$ the following inequalities are satisfied.[12]

$$\gamma_i sgn(s_i)/s_i > \sum_{j=1}^{n} | \dot{M}_{ij}/2 | \tag{3.12}$$

3.3.2 Design of variable structure controller

The control input U to gurantee (3.12) can be obtained from (3.7) and (3.8) as follows:

$$Q\dot{q} - G + MP + U = -\Gamma sgn(S) \tag{3.13}$$

Let

$$Q = \hat{Q} + \Delta Q$$
$$G = \hat{G} + \Delta G \tag{3.14}$$
$$M = \hat{M} + \Delta M$$

where $\hat{Q}$,$\hat{G}$ and $\hat{M}$ are estimated values of Q,G and M. ΔQ, ΔG, and ΔM are modeling errors. Assume the following bounds for ΔQ_{ij}, ΔG_i, ΔM_{ij} and $\Delta \dot{M}_{ij}$

$$| \Delta Q_{ij} | < \bar{Q}_{ij}$$
$$| \Delta G_i | < \bar{G}_i \tag{3.15}$$
$$| M_{ij} | < \bar{M}_{ij}$$
$$| \dot{M}_{ij} | < \tilde{M}_{ij} \qquad i,j = 1,2,\ldots,n$$

We construct control input U as follows:

$$U = U_{eq} + \Delta U$$
$$= -\hat{Q}\dot{q} + \hat{G} - \hat{M}P + \Delta U \tag{3.16}$$

where $U_{eq} = -\hat{Q}\dot{q} + \hat{G} - \hat{M}P$
This control law yields with (3.13) and (3.15)

$$\Delta Q\dot{q} - \Delta G + \Delta MP + \Delta U = -\Gamma sgn(S) \tag{3.17a}$$

or componentwise,

$$\sum_{j=1}^{n}(\Delta Q_{ij}\dot{q}_j - \Delta M_{ij}p_j) - \Delta G_i + \Delta u_i = -\gamma_i sgn(s_i) \tag{3.17b}$$

We construct switched control input u_i by Chen's method as follows.[13]

$$\Delta u_i = -sgn(s_i)\{ \sum_{j=1}^{n}(\bar{Q}_{ij}|\dot{q}_j| + \bar{M}_{ij}|p_j|) + \bar{G}_i \}$$
$$- s_i\sum_{j=1}^{n} (\tilde{M}_{ij}/2) \qquad i = 1,2,\ldots,n \tag{3.18}$$

Substituting (3.18) into (3.16) yields the final, desired control law

$$u_i = -\sum_{j=1}^{n}(\hat{Q}_i\dot{q}_j + \hat{M}_i p_j) + \hat{G}_i$$
$$- sgn(s_i)\{ \sum_{j=1}^{n}(\bar{Q}_{ij}|q_j| + \bar{M}_{ij}|p_j|) + \bar{G}_i \}$$
$$- s_i\sum_{j=1}^{n} (\tilde{M}_{ij}/2) \tag{3.19}$$

The control law (3.19) always satisfies the inequalities (3.12) and the negative definiteness of V can always be guranteed. Therefore we can conclude that the sliding mode on the proposed time-varying sliding manifolds can always be obtained. Note firstly that the control law (3.19) is related to the parameter bounds in a simple fashion so that parameter variations in the plant can be taken into account easily. Secondly, the control law is given for any degree of freedom n of the plant.

4. Numerical examples

Fig.4 shows a two-link robotic manipulator model used by Young[14] in his studies.

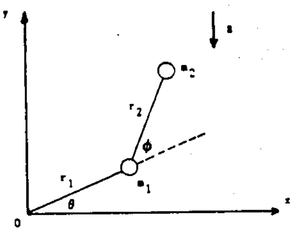

Fig. 1. Two-link robotic manipulator model.

Fig.4 Two-link robotic manipulator model.

The dynamic equation is given by

$$M(q)\ddot{q} + B(q,\dot{q})\dot{q} + G(q) = U \tag{4.1}$$

where $q = [\theta \ \ \phi]^T$

$$M_{11} = (m_1+m_2)r_1^2 + m_2r_2^2 + 2m_2r_1r_2\cos\phi + J_1$$
$$M_{12} = M_{21} = m_2r_2^2 + m_2r_1r_2\cos\phi$$
$$M_{22} = m_2r_2^2 + J_2$$
$$B_{11} = -2m_2r_1r_2\dot{\phi}\sin\phi \tag{4.2}$$
$$B_{12} = -m_2r_1r_2\dot{\phi}\sin\phi$$
$$B_{21} = m_2r_1r_2\dot{\phi}\sin\phi$$
$$B_{22} = 0$$
$$g_1 = -[(m_1+m_2)r_1\cos\theta + m_2r_2\cos(\theta+\phi)]g$$
$$g_2 = -[m_2r_2\cos(\theta+\phi)]g$$

The inertia matrix M(q) is positive definite and symmetric. Parameter values used are the same as those of [14].

$$r_1 = 1\ m,\ r_2 = 0.8\ m$$
$$J_1 = 5\ Kg.m,\ J_2 = 5\ Kg.m,\ m_1 = 0.5\ Kg \tag{4.3}$$
$$0.5\ Kg < m_2 < 6.25\ Kg$$

Note that the value of m_2 is variable due to the payload.

The time-varying sliding manifolds are selected as follows

$$S(e,w,t) = S^o(e,w) + P\begin{bmatrix} t - t_{m1} \\ t - t_{m2} \end{bmatrix}$$

$$= \begin{bmatrix} c_1 & 0 \\ 0 & c_2 \end{bmatrix}\begin{bmatrix} \theta-\theta_d \\ \phi-\phi_d \end{bmatrix} + \begin{bmatrix} \dot{\theta} \\ \dot{\phi} \end{bmatrix}$$

$$+ \begin{bmatrix} p_1 & 0 \\ 0 & p_2 \end{bmatrix}\begin{bmatrix} t - t_{m1} \\ t - t_{m2} \end{bmatrix} \tag{4.4}$$

where p_i and d_i are defined as follows, respectively.

$$p_i = \frac{S_i(\ e(t_o), w(t_o)\ )}{t_{mi} - t_o} \qquad (4.5a)$$

$$d_i = \frac{S_i(\ e(t), w(t)\ )}{(\ 1 + c_i^2\ )^{1/2}} \qquad (4.5b)$$

$$i = 1, 2, \ldots, n$$

According to the values of (4.5b) the sliding manifolds are selected by the following selection mechanism of sliding manifolds.

$$s_i(e,w,t) = \begin{cases} \overset{o}{s_i}(e,w) + p_i(\ t - t_{mi}) & \text{if } d_i > \varepsilon_i \\ \overset{o}{s_i}(e,w) & \text{if } d_i \le \varepsilon_i \end{cases} \qquad (4.6)$$

$$i = 1, 2$$

From the discussion of section 3, we have

$$\bar{Q} = \begin{bmatrix} 18.63c_1 + 10|\dot\phi| & 8.28c_2 + 5|\dot\phi| \\ 8.28c_1 + 5|\theta| & 3.68c_2|\theta| \end{bmatrix} \qquad (4.7a)$$

$$\tilde{M} = \begin{bmatrix} 10|\dot\phi| & 5|\dot\phi| \\ 5|\dot\phi| & 0 \end{bmatrix} \qquad (4.7b)$$

$$\bar{M} = \begin{bmatrix} 18.63 & 8.28 \\ 8.28 & 3.68 \end{bmatrix} \qquad (4.7c)$$

$$\bar{G} = [\ 101.43 \quad 45.08\ ]^T \qquad (4.7d)$$

The control inputs are constructed as follows

$$u_1 = u_{eq1} + sgn(s_1)[\ \bar{Q}_{11}|\dot\theta| + \bar{Q}_{12}|\dot\phi| + \bar{M}_{11}|p_1| + \bar{M}_{12}|p_2| + \bar{G}_1\ ] - s_1(\ \tilde{M}_{11} + \tilde{M}_{12}\ )/2 \qquad (4.8a)$$

$$u_2 = u_{eq2} + sgn(s_2)[\ \bar{Q}_{21}|\dot\theta| + \bar{Q}_{22}|\dot\phi| + \bar{M}_{21}|p_1| + \bar{M}_{22}|p_2| + \bar{G}_2\ ] - s_2(\ \tilde{M}_{21} + \tilde{M}_{22}\ )/2 \qquad (4.8a)$$

Fig.5 and Fig.6 show the phase diagrams for the proposed time-varying sliding manifolds in the presence of payload change.

5. Conclusions

In order to remove reaching phase, the time-varying sliding manifolds are introduced. By the proposed method in this paper the sliding modes can always be guaranteed during the overall control process and so the system has robust performance. Therefore parameter variations in the plant can easily be coped with , and load forecast is not needed. The simple design procedure encourages control engineers to implement the proposed variable structure control algorithm in many control problems.

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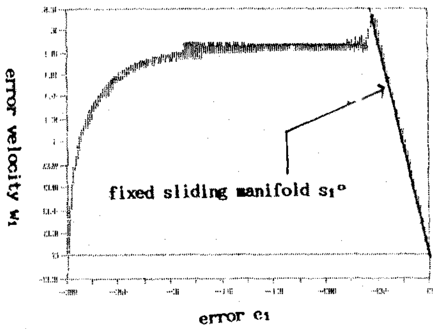

Fig.5 Phase diagram for e_1 and w_1

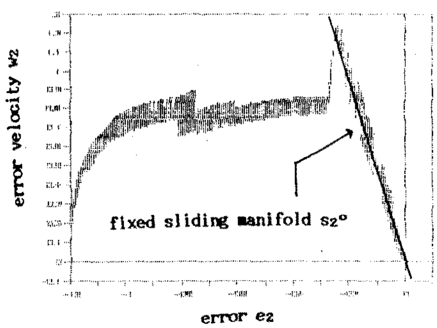

Fig.6 Phase diagram for e_2 and w_2