ROBOTS FOR CLEANING AND DECONTAMINATION OF BUILDING CONSTRUCTIONS.

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ABSTRACT

Some important problems of building maintenance is cleaning of walls, ceilings and floors, cleaning of window glasses in high rise office buildings. The problem is specially advanced for application in nuclear power station halls, underground stations etc. Robotic systems for these purposes consist of mobile robot having horizontal motion with wall climbing robot installed on its body. Each robot is supplied with cleaning instruments. Wall climbing robot has possibility to be attached and detached with horizontal motion robot at full automatic mode. In addition to that it should be always ensured that the climbing robot at its working zone is placed in the most stable posture so that the vacuum created inside the gripper will be minimum to avoid surface damage. In this paper a method has been addressed for finding most stable posture for the robot body for a particular gripping position. Also some results of testing and experimental investigations of the floor and wall cleaning robotic system have been presented.

1. INTRODUCTION

The application of climbing robot(CR) is increasing day by day in the fields of different construction and maintenance operations: such as internal and external wall cleaning, ceiling and floor cleaning, window glass cleaning in high rise office building etc. The application is specially important for the periodic maintenance work inside nuclear power stations.

Design and development of vacuum leg type climbing robot has been discussed in [1] which is suitable for construction purposes. Discussions were presented for climbing type of inspection robot and climbing robot having magnetic legs in [2,3].

Main principles of designing robotic complex of vertical climbing type has been discussed in [4]. Motions of CR under external disturbances have been presented in [5].

In this paper a robotic system capable of cleaning floors and walls with high degrees of mobility and reliability has been presented. In general for reliable contact on the vertical wall the CR may have different kinematic schemes, one of which has been shown in [1]. A climbing robot with vacuum paws remain attached with the vertical wall in a similar way like a lizard.

When robot starts its technological operations in any goal position the creation of vacuum to keep the robot body in equilibrium will depend on its posture. It is very important that before starting technological operations robot body must be held in most stable posture. So far a number of research work for generation of stable grasping strategies[6,7,8,9] have been carried out. But all are devoted to multi fingered robot hands in manipulating type of robots. However, in this paper stable grasping strategies for CR based on two quality measures: structured twist space quality measure(T_q) and structured wrench space quality measure(R_q), have been found out. Other quality measures may also be included [10], but for simplicity and to illustrate the principle here the stable grasping strategy based on T_q and R_q have been considered.

2. CONSTRUCTION OF ROBOTIC SYSTEM FOR CLEANING AND DECONTAMINATION

The whole complex of the robotic system has been shown in fig 1, where 1 is horizontally moving robot (HMR), 2 is climbing robot, 3 & 4 are technological equipment(vacuum cleaners)mounted on the HMR and CR respectively, 5 is the manipulator for attaching and detaching the CR with HMR, 6 is the actuating devices, 7 is the controlunit, 8 is the operator, 9 is the control channel, 10 is the horizontal surface to be cleaned, 11 is the vertical surface to be cleaned.

HMR is a automatically guided vehicle for carrying manipulator for specific technological operation. HMR has the capability of moving not only on even surfaces but also on the uneven rough surfaces for the special design of wheels mounted on it. For controlling HMR in ambiguous environments the ultrasonic sensors are mounted on the body of the HMR. This proximity sensor helps the robot in navigation in cluttered environment and to find out specific objects such as doors of a room etc.

Vacuum cleaners are mounted below the platform of the HMR to enable it to clean the floors on its way of movement.

During the horizontal motion the CR remains idle and is being held firmly by the gripper of the manipulator mounted on HMR. When it reaches near the vertical wall the sensor gives necessary signals to the HMR controller to detach CR from its gripper and the manipulator attach the CR with the wall surface. After this the CR becomes functional and starts working in automatic mode for cleaning the vertical wall with vacuum cleaners attached with the CR.

The actuating device feed the CR grippers and also the vacuum cleaners through cable. The trajectory of the CR is controlled by the control unit in the programming mode.

The presence of contamination is sensed by the special sensory devices and guide the CR towards it for decontamination. After cleaning is over the CR returns to its initial position and from there it is taken back to its original position by the manipulator of the HMR. The experimental result shows that the positional accuracy of detaching the CR from HMR and attaching the CR after technological operation is over and returning to its original position is $\pm$150mm.

The operator can monitor over the system from the video-display unit and edit the programme to change the movements of the robots if necessary. The control channel may of be wire type or wireless type. For the present complex the maximum distance between the operator and the end point of the complex is 60 M. There is a special system for winding and rewinding the cable, so that it cannot create any problem during movement.

The photographic view of the whole complex has been shown in the fig 2. Experimental results shows that the system is characterized by its reliability and mobility.

3. MODELLING OF ORIENTATION AND MOTION OF TRANSPORT MODULE OF HMR

Before the development of real robotic system, modelling of orientation and movement of HMR is needed to enable it to operate in a smooth and reliable manner. The main difficulty lies in the fact that the environment where the system will work is quite often undefined. To solve this problem fuzzy logic is introduced here.

It is the logic by which human being drives car. The methodology is presented in [10]. It is applicable to any complex process which is too difficult for modular control using conventional methods or the control of which is relied upon the experience of the human operator.

In this part of the article the fuzzy control of HMR with rule based fuzzy controller has been discussed. Control rules are derived by modelling an expert driving action. There are three methods of achieving a linguistic set of fuzzy rules which represent a systems input-output behavior:verbalization, fuzzification and identification.

Here we have used fuzzification and identification methods. The following fuzzy control rules are used for multiple input and single output controller [11].

$$R^i : X_1 \text{ is } A_1^i \; X_2 \text{ is } A_2^i \ldots\ldots X_n \text{ is } A_n^i \rightarrow Y^i = p_o^i + p_1^i X_1 + p_2^i X_2 + p_3^i X_3 + \ldots\ldots\ldots\ldots + p_n^i X_n, \tag{3.1}$$

Where A_j^i's are fuzzy variables and Y^i is the output of i th control rule determined by a linear equation with coefficients p_i^j. The membership function of a fuzzy set A is composed of straight lines. When the inputs X_i^o - X_n^o are given ,the true value of the premise of i th rule is calculated as

$$W^i = \min_{j=\overline{1,n}} A_i^j(X_j^o), \tag{3.2}$$

where A(X) is a membership function of fuzzy sets A and the output Y^o is inferred from m rules by taking the weighted average of the Y's as

$$Y^o = \sum_{i=1}^{m} W^i Y^i / \sum_{i=1}^{m} W \tag{3.3}$$

Identification algorithms of fuzzy control rules are given in [10-13]. The reasoning methods are described in [10,12]. A fuzzy set in a consequence of a rule has a monotone member ship function and defuzzification is computed as a weighted mean [12]. The logical connections are made in our system using only AND,OR and NOT gates. The fuzzy sets are represented as (L-R) type flat fuzzy numbers. About 500 input-output data have been taken from eighteen trajectories and four variables X_1, X_2, X_3, X_4 have been chosen as shown in the fig 3.

Here X_1 is the distance from entrance of the corner,X_2 is the distance from inner wall,X_3 is the direction (angle) of robot, X_4 is the distance from outer wall. Expert driving action are modelled in the form of 20 control rules.

We choose three fuzzy variables for X_1 ,two for X_2,three for X_3 and one for X_4 by observing the expert's actions. For a given input-output $X_{1K}, \ldots\ldots X_{nK}$, Y_K are taken from operator's control action. As in [11,12] we have to identify :1)the number of fuzzy partitions of the input space(for example small,medium and large for X_1 ;small and large for X_2 etc.);2)the membership functions of those fuzzy variables;3)the coefficients in the consequence of the rules the number of which is {mx(n+1)}. The coefficients (p_o^i-p_n^i)are easily identified using the output of (3.3). To minimize the output error (for example as in [11]) the so called stable Kalman filter can be used.

Fig. 4 shows the results of the simulation of HMR on microcomputer. The programs and algorithms of simulation have been described in [13]. The result shows that the described control rules worked very well.

4. ANALYSIS OF STABLE GRASPING STRATEGY FOR CLIMBING ROBOTS

Contact kinematics and transformation relations: Let us attach the following co-ordinate frames as shown in the fig 5.

C_W =The inertial frame, i.e., the reference frame attached to the wall

C_R =The body co-ordinate frame attached with the C.G. of the robot body

C_{li} =The leg co-ordinate frame attached with the last link of the leg

C_{Li} =The local co-ordinate frame attached with the i th point of contact with the leg to the wall.

C_{Wi} =The instantaneous fixed co-ordinate with relative to the wall attached at the i th point of contact.

Note: The Z axis of C_{Li} and C_{Wi} coincide, ϕ is defined to be the contact angle relative to the two X axes. This is the function of contact geometry.

Now it is well known that the operator $T(w)=\begin{bmatrix} o & -w_3 & w_2 \\ w_3 & o & -w_1 \\ -w_2 & w_1 & o \end{bmatrix}$, where $w=\begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix}$, when operated on the radius vector $\{f\}_s=\begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix}$ gives the following results $T(w)\{f\}_s=\{wxf\}_s=-\{fxw\}_s$; Using this result and transformation principle we have deduced the force/torque and velocity transformation relations between robot body to leg tips and leg tips to the leg joints. The results have been summarized below and shown in the fig 6.

	Force/Torque Relations	Velocity Relations
Robot body to leg tips	$\begin{pmatrix} F_{CR} \\ M_{CR} \end{pmatrix}=GX$	$\xi=G^t\begin{pmatrix} V_{CR,C\omega} \\ W_{CR,C\omega} \end{pmatrix}$
Leg tip to leg joints	$\tau=J_l^t(\Theta)X$	$\xi=J_l(\Theta)\dot{\Theta}$

Where G =Grasp matrix,
X =The contact wrench,
ξ =The contact velocity vector,
$J_l(\Theta)$ =Leg Jacobian of the robot.

with this background we shall now try to evaluate the two quality measure T_q and R_q

4.1 GRASP PLANNING There are two main steps for grasp planning 1)selecting a good grasp on the wall,2)using the co-operative action of the legs to take the robot body in proper grasping position.

However, in this paper we shall study how to generate the good grasp based on two quality measures;twist space quality measure and wrench space quality measure. Then the performance is being measured by constructing the performance measurement function{PM=f(T_q,R_q)} like

$PM=T_q^{\gamma}.R_q^{1-\gamma}$.....(4.1.1),where the value of γ will depend on the type of work the system will perform.

As for example,for stable grasping function, more weightage should be given to wrench space quality measure rather than manipulability quality which is characterized by twist space quality measure T_q. We have chosen the value of γ as 0.2.

Our next step is to evaluate T_q and R_q. Let us model the gripping task by two task ellipsoids E_T and E_R ,one in twist space and another in the wrench space. Also let us assume stiffness control is

$* \sigma_i = K_i \delta_i$,

used for the robot legs. Hence for leg σ_i is related to δ_i by * where K_i is the desired stiffness in the direction D_i = the task direction expressed in body co-ordinate.

In the generalized form we can represent $E_T = \alpha E_1 X + c$ (4.1.2) and $E_R = \beta E_2 X + d$ (4.1.3) where α and β are the scaling parameters responsible for the size of the ellipsoids and E_1 and E_2 are the structured matrix given by

$$E_1 = [D_1 \dots D_6] \begin{bmatrix} \delta_1 & \dots & 0 \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ 0 & \dots & \delta_6 \end{bmatrix} \begin{bmatrix} D_1^t \\ \cdot \\ \cdot \\ D_6^t \end{bmatrix} = D \delta D^t \quad (4.1.4)$$

$$E_2 = [D_1 \dots D_6] \begin{bmatrix} \sigma_1 & \dots & 0 \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ 0 & \dots & \sigma_6 \end{bmatrix} \begin{bmatrix} D_1^t \\ \cdot \\ \cdot \\ D_6^t \end{bmatrix} = D \sigma D^t \quad (4.1.5)$$

$X, c, d \in R^6$, $|X| \le 1$; for simplicity we shall assume $c = d = 0$.

Structured twist space quality measure T_q: Let us assume an unit ball in R^m ($O_1^m \subset R^m$), the space of leg joint velocities, and define the structured twist space quality T_q by

$$T_q = \sup_{\alpha \in R} \left\{ \alpha, \text{such that } J_l (O_1^m) \supset G^t(E_T) \right\} \quad (4.1.6)$$

The physical meaning of T_q is as follows: The unit ball O_1^m in the leg joint velocity space is mapped into the space of contact velocity by J_l. On the other hand, gripping task ellipsoid is mapped back into the contact velocity space by G^t. T_q is then the largest α such that $G^t(E_T)$ is contained in $J_l(O_l^m)$ (ref. fig.7). In other words the robot body velocity of size α can be accommodated by leg joint velocity of unit magnitude. Theoretically T_q is the ratio of structured output (the task ellipsoid) over the input (i.e. the leg joint velocity).

From fig.7, it is evident that T_q is at its maximum if the inner ellipsoid has the same size and orientation as the outer ellipsoid.

Now using the expression $J_l(O_l^m) = \alpha E_1 X \in R^n$, $\langle \alpha E_1 X, (J_l J_l^t)^{-1} \alpha E_1 X \rangle \le 1$

and $G^t(E_T) = \left\{ \alpha G^t E_1 X \in R^n : X \in R^6 \ |X| \le 1 \right\}$

From (4.1.6), we have $G^t(E_T) \subset J(O_1^m)$, if and only if $\langle \alpha G^t E_1 X, (J_l J_l^t)^{-1} \alpha G^t E_1 X \rangle \le 1$

for all $|X| \le 1$, or, $\alpha^2 \sup \langle G^t E_1 X, (J_l J_l^t)^{-1} G^t E_1 X \rangle \le 1$

or, $\alpha^2 \sup \langle X, (G^t E_1)^t (J_l J_l^t)^{-1} G^t E_1 X \rangle \le 1$, which is

equivalent to $\alpha \le \sigma_{max}^{-1/2} \left\{ E_1^t G (J_l J_l^t)^{-1} G^t E_1 \right\}$. (4.1.7)

or, $\alpha \le \sigma_{max}^{-1/2} M$ where $M = \left\{ E_1^t G (J_l J_l^t)^{-1} G^t E_1 \right\}$ and $\sigma_{max} M$ is the maximum singular value of the matrix M. Hence from (4.1.6), $T_q = \sigma_{max}^{-1/2} M$. (4.1.8.a)

Structured wrench space quality measure R_q: To evaluate wrench space quality R_q let $O_1^n \subset R^n$ be the unit ball in the leg wrench space and $\sigma_{max}(J_l)$ be the maximum singular value of J_l. We define the structured wrench space quality

$$R_q = \sup_{\beta\in R} (\beta, \text{ such that } G(O_l^n \supset E_R).\sigma_{max}^{-1}(J_l) \quad (4.1.9)$$

The physical meaning of R_q has been elaborated in the fig.8. As before it can be evaluated as

$$R_q = \sigma_{max}^{-1/2}\left\{E_2^t (G^t G)^{-1} E_2).\sigma_{max}^{-1}(J_l)\right\}$$

$$= \sigma_{max}^{-1/2} N \text{ where } N = E_2^t (G^t G)^{-1} E_2.\sigma_{max}^{-1}(J_l)$$

(4.1.8.b)

4.2 DETERMINATION OF STABLE POSTURE

After calculating the matrices M and N, T_q and R_q can be evaluated by the singular value decomposition data of the matrices. Then the PM incorporating T_q and R_q is to be evaluated. Then we will have to draw the following curves: Posture(θ_{ij}) vs.T_q; θ_{ij}vs.R_q and θ_{ij}vs.PM, and we shall select that posture (θ_{ij}) corresponding to what T_q, R_q and PM will be maximum.

4.3 EXAMPLE AND SIMULATION For simplicity let us consider a two dimensional model.(ref. marked part of fig. 5.). Let 1) the contact be modelled as point contact with friction, 2) the leg spacing be of 2 unit, 3) G is fixed as shown in the fig.5, 4) the robot body is constrained to move vertically. This leaves the system with a single degree of freedom. Let θ_{ij} be the generalized co-ordinate of the system and we study how θ_{ij} affects the structured grasp quality measure.

Construction of grasp matrix G:

Steps which are to be followed for constructing the grasp matrix are 1)specify a body co-ordinate and obtain the co -ordinates of each contacting point;2) determine the unit normal and two orthogonal tangent vectors to the contacting surface at the contact point; 3)pick up a torque origin in body co ordinates and construct for each contact map the contact matrix;4) join the contact matrices side by side into a big matrix.This is the grasp matrix for the particular choice of the body co-ordinates and the particular choice of the torque origin.

Computation for leg Jacobian:

$$J_L = \text{Leg Jacobian} = \begin{pmatrix} J_{L1} & 0 \\ 0 & J_{L2} \end{pmatrix}$$

where $J_{L1} = \begin{pmatrix} \text{Cos}\,\alpha & -\text{Sin}\,\alpha \\ \text{Sin}\,\alpha & \text{Cos}\,\alpha \end{pmatrix}\begin{pmatrix} -\text{Sin}\,\theta_{11} & -\text{Sin}(\theta_{11}+\theta_{12}) & -\text{Sin}(\theta_{11}+\theta_{12}) \\ \text{Cos}\,\theta_{11} & \text{Cos}(\theta_{11}+\theta_{12}) & \text{Cos}(\theta_{11}+\theta_{12}) \end{pmatrix}$

$$J_{L2} = \begin{pmatrix} -\text{Cos}\,\alpha & \text{Sin}\,\alpha \\ -\text{Sin}\,\alpha & -\text{Cos}\,\alpha \end{pmatrix}\begin{pmatrix} -\text{Sin}\,\theta_{21} & -\text{Sin}(\theta_{21}-\theta_{22}) & \text{Sin}(\theta_{21}-\theta_{22}) \\ \text{Cos}\,\theta_{21} & \text{Cos}(\theta_{21}-\theta_{22}) & \text{Cos}(\theta_{21}+\theta_{22}) \end{pmatrix}$$

where α =the orientation angle of the robot body=0;other constrains are $\theta_{12} = \pi - 2\theta_{11}$, $\theta_{21} = \pi - \theta_{11}$, and $\theta_{11} - \theta_{22} = \pi - (\theta_{11} + \theta_{12})$

Other computations : Value of $K = \begin{pmatrix} 10 & 0 & 0 \\ 0 & 190 & 0 \\ 0 & 0 & 100 \end{pmatrix}$ D=I ,Unit matrix.

$\delta = \text{diag}\left\{0.8 \quad 0.7 \quad 0.02\right\}$;

$\sigma = \text{diag}\left\{8 \quad 133 \quad 2.\right\}$.

With reference to the marked part of fig.5,for two contact points the grasp matrix

$$G = \begin{pmatrix} -1 & 0 & 1 & 0 \\ 0 & -1 & 0 & 1 \\ 0 & -1 & 0 & -1 \end{pmatrix}$$

Knowing D, δ & σ ,Structured matrices E_1 & E_2 can be computed from (4.1.4) & (4.1.5),hence we can calculate T_q & R_q from (4.1.8.a) & (4.1.8.b) respectively by singular value decomposition data of M and N. Fig.9 shows plots of quality measure and the performance measure as a function of θ_{11}.It is evident from this figure that the optimal posture of CR is corresponding to the position A where θ_{11}=0.7 radian=40 degrees approximately.

5.CONCLUSIONS

The mobile complex including horizontal moving robot and climbing robot has got tremendous practical applications in the fields of building construction.As a future work,for reliable functioning of such complex in real environment,several sensory devices together with the development of mathematical models for different variants of the system and the elements of artificial intelligence are to be incorporated.This will give the possibility to control the robotic complex with high accuracy,to test the quality of the technological operation and to enable the robotic system to work in an undefined environment.

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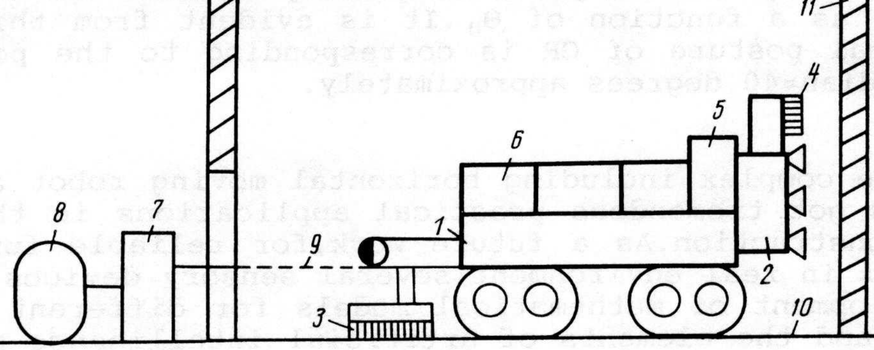

Fig. I Robotic system complex.

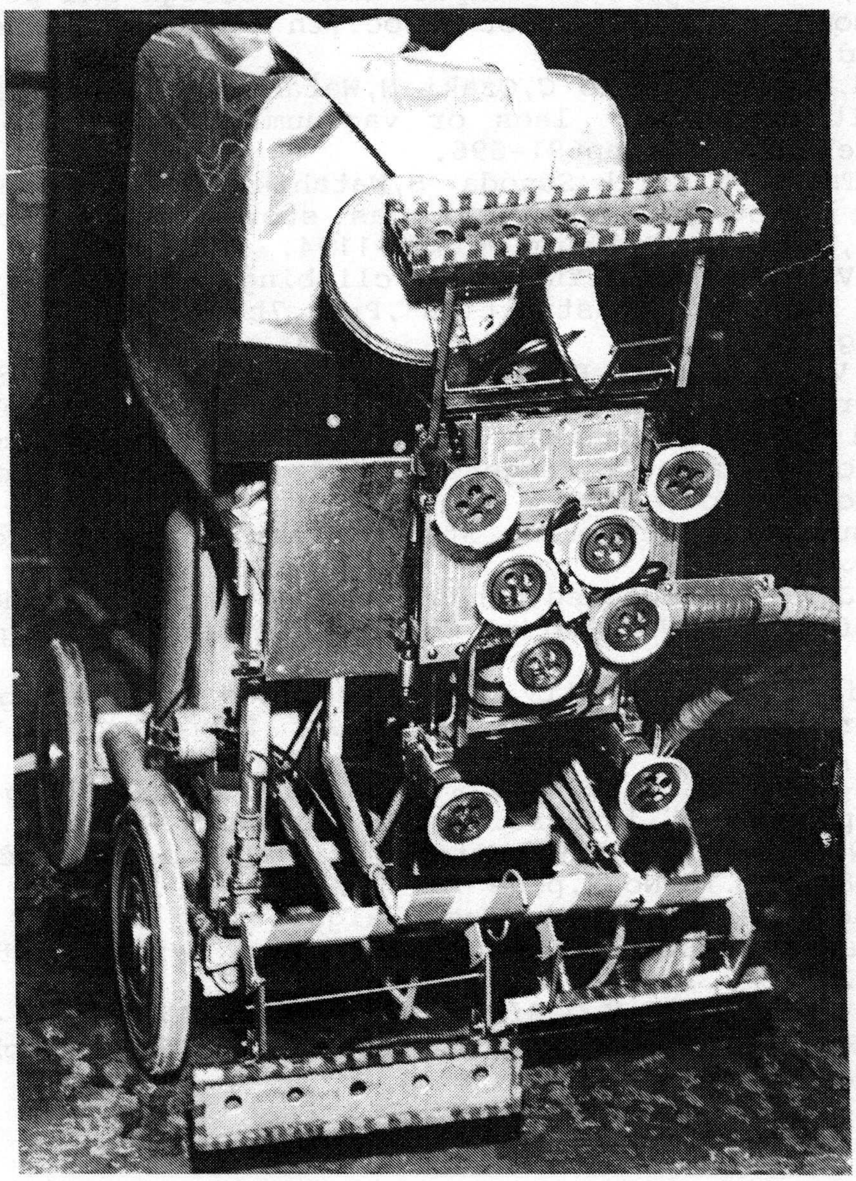

Fig.2 Photographic view of the robotic complex.

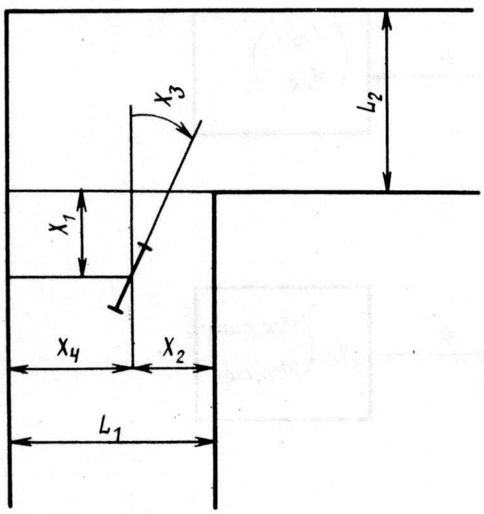

Fig. 3

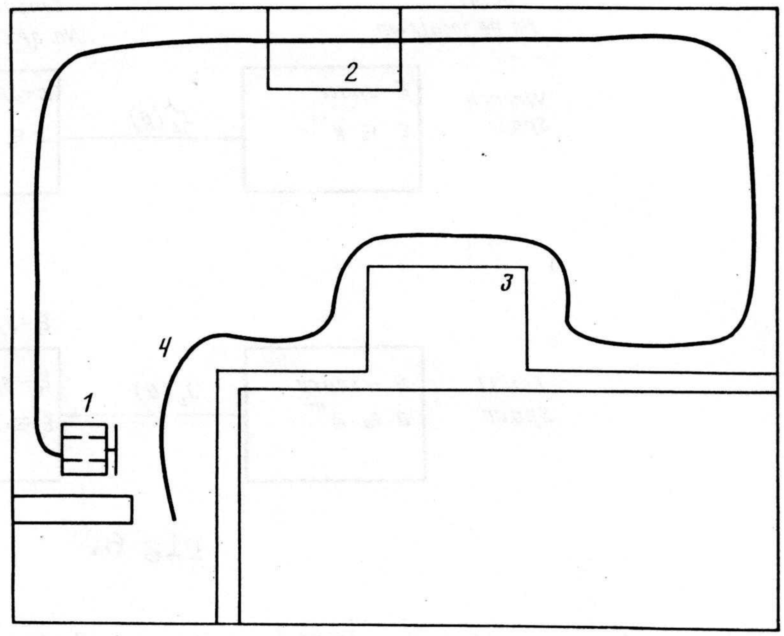

Fig. 4 Results of simulation of HMR, I- HMR, 2- surface to be cleaned, 3- obstacle, 4-Trajectory of HMR.

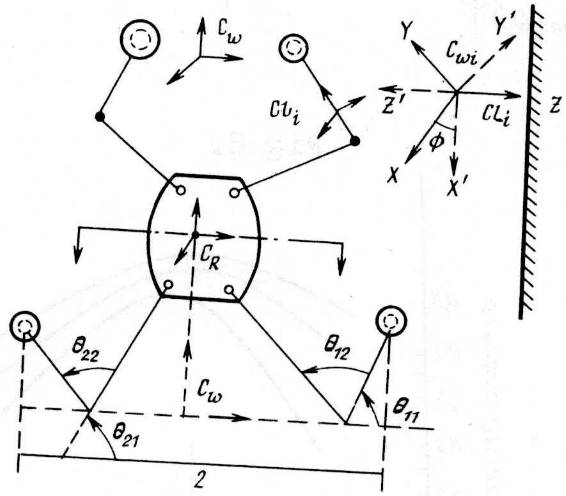

Fig. 5 Co-ordinate system of climbing robot.

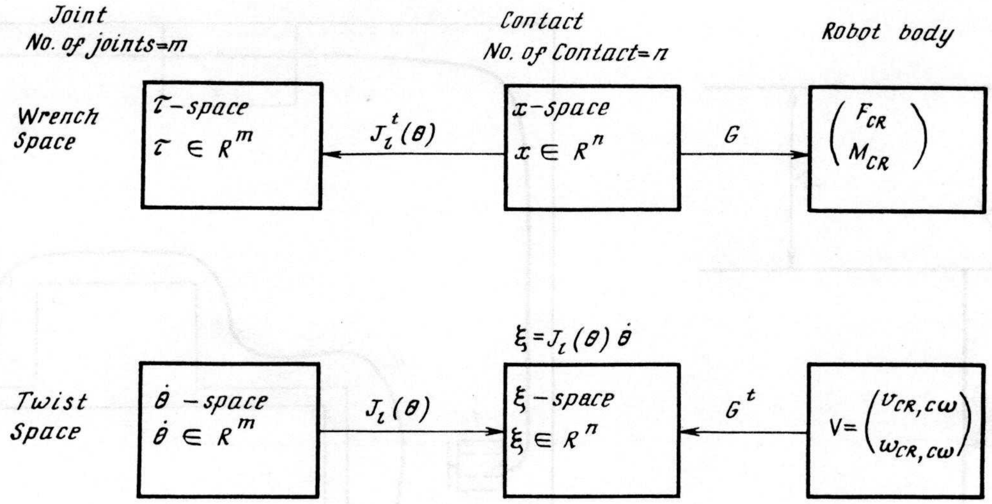

Fig 6.

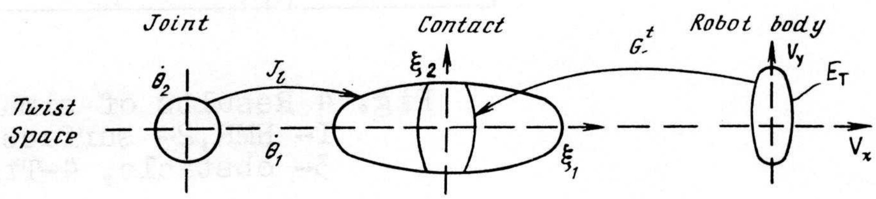

Fig 7.

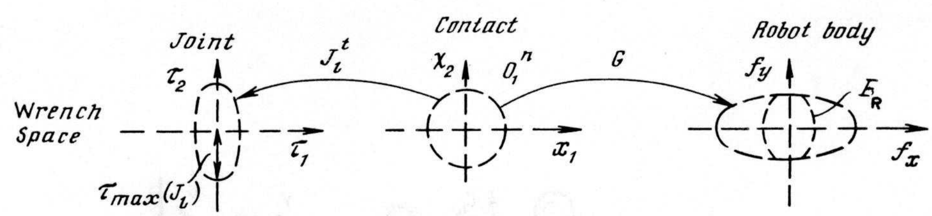

Fig 8.

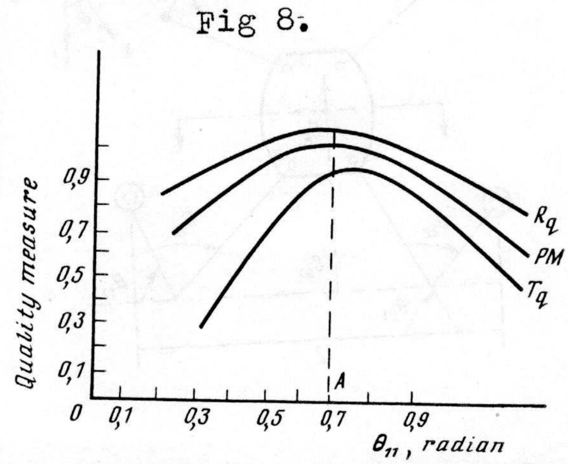

Fig 9.