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Self Calibration of Step-by-Step Based Climbing Robots

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Abstract— **Fine manipulation of large industrial manipulators faces many problems due to well known error sources. Most climbing robots can be seen as mobile manipulators whose base is also moving across the climbing structure, and consequently adds some additional positioning errors. 3DCLIMBER is a serial mechanism pole climbing robot, developed at ISR-UC. The preliminary tests of the robot showed that it is particularly important to position the grippers precisely in the appropriate pose before grasping the structure. Otherwise the accumulating error will impair autonomous climbing process by forcing the operator to stop the operation after a couple of steps in order to calibrate the robot. This paper describes a self calibrating method proposed to measure and compensate these errors.**

I. INTRODUCTION

Development of climbing robots was a challenging area during the last decade. Different types of climbing robots were developed either for climbing over flat or curved surfaces. For holding robots attached to a smooth surface, suction cups [3], [4], [5] or magnets [6], [7] were used. Robots, whose end-effectors match engineered features of the environment like fences or porous materials or bars [8], [10], [11] were developed. Robots for climbing inside pipes or ducts [12], [13] or climbing over poles [15], [16], [17], [18], [19] were also developed. The latter group is called Pole Climbing Robots (PCRs). Previously developed PCRs were based on either continuous or step-by-step based climbing mechanisms. Continuous motion PCRs [18], [20] which use tires both for climbing and gripping to the pole are faster and lighter than step-by-step motion PCRs. Their main drawback is the lack of maneuverability. These kinds of robots are mostly appropriate for climbing over simple poles and performing simple tasks which don't need a manipulator, like washing the poles. On the other hand, if one robot aims to perform more complicated tasks, like welding, testing or painting of pipes, a step-by-step based design is a better choice. The reason is that this type of robot takes advantage of its separate gripping and climbing modules which result in more stability on the pole as well as better maneuverability. All step-by-step based PCRs have one common aspect. They have two grippers on two sides which are connected through a multi DOFs climbing mechanism. The climbing mechanism might be serial [21], [22], hybrid (serial-parallel) [17] or parallel [15]. In all these robots, to take each step, one gripper grasps the structure and acts as the base of the robot, while the other gripper acts as manipulator. Therefore, if the base is not well positioned before grasping, or if its position and angle change after grasping, the error on the base will cause an error on the manipulator, since the movement of the manipulator is relative to the base. This error, along with other error sources which will be described in this paper, will remain with the manipulator in the next step in which the manipulator changes its role as base of the robot. If this error is not compensated, it will accumulate in each step. Consequently, we concluded that an algorithm for autonomous self calibration and error compensation is necessary.

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II. PROBLEM STATEMENT

Our preliminary tests on the 3DCLIMBER showed that small errors on positioning of the gripper before grasping the structure will result in an overly defined system [22], because the gripper tries to grasp the structure while it is not well positioned. Thus, even if the gripper succeeds in grasping, the actuators of the climbing mechanism will try to compensate the error, pulling maximum current, and consequently overheating. Therefore, precise positioning and gripping is necessary and such errors must be compensated in each step. Adding to all the fore mentioned problems, this error is accumulative and the total deviation from the desired position and angle becomes increasingly larger after each step, making it impossible to grasp the structure and continue the movement after a couple of steps. Therefore, the operator has to stop the operation, manually calibrate the robot and then resume the operation. Furthermore, an important advantage of step-by-step based climbing robots over the wheel based climbing robots is their better maneuverability due to the existence of a robotic manipulator and such advantage becomes more outstanding if the manipulator can perform fine manipulation. Fine manipulation is necessary for some maintenance applications (e.g. the light bulb changing operation) and if the manipulator can perform fine manipulation, the necessity of integrating a separate arm can be abolished. However as it will be described later, fine manipulation with large manipulators can not be done only with internal motor encoders and requires external feedbacks to compensate positioning errors. This paper suggests an algorithm for the compensation of such errors. The general stated problem exists for many step-by-step based PCRs and the solution is valid for most of them with some variations in the formulations. The solution which is presented in this paper was successfully tested on the 3DCLIMBER robot. The 3DCLIMBER robot includes a 4DOF mobile robotic arm. Error sources which are cause of the mentioned problems can be divided into two main groups:

- General error sources of industrial robotic arms.
- Error sources due to mobility of the arm base.

A. General error sources of industrial robotic arms

High accuracy is generally difficult to obtain in large manipulators capable of producing high forces due to system elastic and geometric distortions [23]. Due to some sources of errors, namely tolerance on gears, coupling errors, deflection of the links, etc, the manipulator has positioning errors. This is a general problem of the robotic arms which has been discussed in the literature. For instance, the control problem of flexible link robotic manipulators has been studied in the last two decades [24]. Some control strategies (i.e. fuzzy and adaptive control) have been proposed [25]. To measure the amount of the deflection, two strain gauges are usually stuck onto the arm [25]. Most manipulator calibration techniques require expensive and/or complicated pose measuring devices, such as theodolites [26].

As the 3DCLIMBER consists of a relatively large robotic arm, the same problem of fine manipulation in large manipulators exists. This error should be compensated after making a step forward and before gripping the structure. It should be mentioned that the robot is not designed by flexible link concept and is a rigid link arm. But, high torques on joints (up to $200 N.m$) cause small deflections on aluminum links which are not avoidable as they produce big errors on the manipulator pose, when multiplied by large values (length of the links).

B. Error sources due to mobility of the robot's base.

In industrial robotic arms, the base of the robot is usually fixed to a certain point. A step-by-step based climbing robot usually consists of a climbing mechanism and two grippers [14], [21], [22]. During climbing, the gripper which is fixed is called "Base" and the other gripper which is moving is called "Manipulator". The base and the manipulator change their role in each step and as the manipulator movements are programmed relative to the base, errors in pose of the base will cause errors in pose of the manipulator. The left picture in figure 1 shows the robot status without error, and the right figure shows the status after the error occurs. Here, the lower gripper (G2) is the base. Due to the errors, the lower gripper is not perpendicular to the structure which causes errors on X, Z and angle of the manipulator (Figure 5). As stated, these errors impair the robots autonomous climbing process and should be compensated on each step of the movement and right before grasping the pole. For simplicity of referencing in the following sections of the paper, the errors related to the general errors of the industrial robotic arms are called "Type A" Errors and those related to the mobility of the robot's base are called "Type B" Errors.

III. 3DCLIMBER ROBOT

The 3DCLIMBER robot (figure 2) consists of an upper and lower gripper and a 4DOFs serial arm as climbing mechanism. The 4DOFs mechanism (figure 3) consists of a 3DOFs serial arm and a rotation guide. The inverse kinematics formulation of the mechanism is necessary for the trajectory generation. The straight line trajectory generation algorithm of the 3DCLIMBER calculates the trajectory which falls inside a specified tolerance from the ideal straight path 1. More information about the robot can be found in [22].

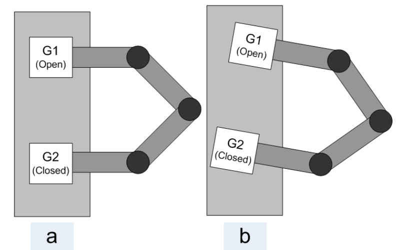

Fig. 1. Errors on the positioning of the base of the robot cause error on the manipulator of the robot

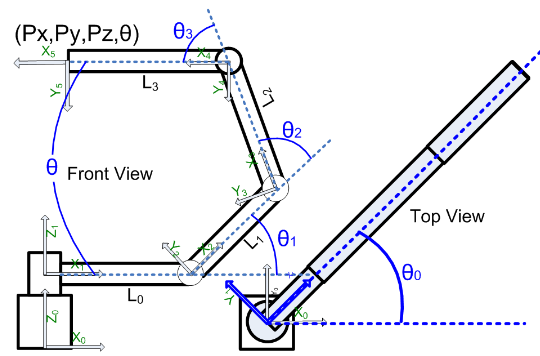

Fig. 3. Schematic of the 4 DOFs serial climbing mechanism

The inverse kinematics problem is necessary for the trajectory generation algorithm. The inputs of the trajectory generation algorithm are the current and desired poses of the manipulator relative to the base of the robot, the desired task space trajectory which should be followed (usually one or a sequence of straight lines), and the desired "path following" precision. The trajectory generation algorithm, which is based on the Taylor straight line planning method [27] calculates the minimum number of intermediate points between the poses which guarantees the required precision. It then uses the inverse kinematics to generate the joint space trajectory. Algorithm 1 shows the trajectory generation and execution algorithm based on the Taylor method. The inverse kinematics problem, have two solutions. θ_{21} is the first solution for θ_2 and θ_{22} is the second solution for θ_2. Definition of other parameters can be seen in figure 3:

$$\theta_0 = \arctan 2\frac{P_y}{P_x} \tag{1}$$

$$\theta_{21} = \arctan 2(+\sqrt{1-Q^2}, q) \;\;\&\;\; \theta_{22} = \arctan 2(-\sqrt{1-q^2}, q) \tag{2}$$

$$\theta_{11} = \arctan 2(P_z, c_0 P_x + s_0 P_y - l_0) - \arctan 2(K_{21}, K_{11}) \tag{3}$$

$$\theta_{12} = \arctan 2(P_z, c_0 P_x + s_0 P_y - l_0) - \arctan 2(K_{22}, K_{11}) \tag{4}$$

$$\theta_{31} = \theta - \theta_{11} - \theta_{21} \;\;\&\;\; \theta_{32} = \theta - \theta_{12} - \theta_{22} \tag{5}$$

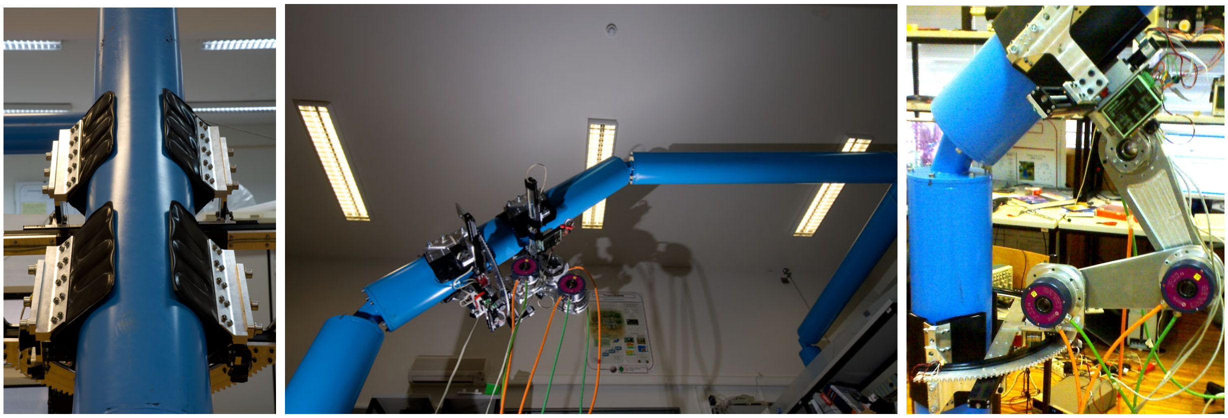

Fig. 2. Snapshots of the 3DCLIMBER

Where:

$$q = \frac{P_x^2 + P_y^2 + P_z^2 - 2l_0\sqrt{P_x^2 + P_y^2} + l_0^2 - l_1^2 - l_2^2}{2l_1 l_2} \tag{6}$$

$$K_{11} = l_1 + l_2 c_{21}, K_{21} = l_2 s_{21} \;\;\&\;\; K_{12} = l_1 + l_2 c_{22}, K_{22} = l_2 s_{22} \tag{7}$$

IV. Solution

To address the fore mentioned problems, an autonomous self calibration algorithm is proposed in order to compensate the errors and calibrate the system in each step of the robot's movement. This algorithm requires the absolute pose of each link, in order to calculate and compensate the previously mentioned errors. The absolute pose of each link can be obtained with different strategies, namely by triangulation or by trilateration to a fixed reference system. In both cases, a reference base station is required and should be calibrated before starting the robot operation. This might not be a practical solution for outdoor industrial applications as the installation and calibration of the observer is a time consuming task requiring an expert. Since the 3DClimber robot is intended to operate in multiple structures and places, a solution which is embedded into the robot is highly preferred. Therefore, the proposed solution is based on an algorithm in which the absolute inclination of the links (inclination of each link relative to the horizontal) and distance of the manipulator to the structure should be measured. This method does not provide the absolute position of the robot on the structure, but it provides a precise relative pose of all links which does not contain the fore mentioned error source. Consequently, all mentioned errors can be calculated and compensated. Inclinometer and range finder sensors which have been used for this purpose will be described in the next section. These sensors will provide external feedback for the positioning system. In the proposed algorithm, each step of the movement is composed of three phases. In the first phase, the manipulator moves from its current pose $P_c = (Xc, Yc, Zc, \theta_c)$ to a desired pose $P_d = (Xd, Yd, Zd, \theta_d)$ without any error compensation algorithm involved. In the second and third phases of each step, Type A and Type B Errors will be compensated.

A. 2^{nd} Phase of Each Step: Compensation of Type B Error

The error on the placement of the base generates a relative error on the manipulator which is shown in Figure 5. In this phase, sensors will measure the angle deviation error of the robot's base $(\delta\theta)$, and, consequently, using the trajectory generating algorithm, the position of the manipulator will be changed from P_d to $P_d + (-\delta X, 0, \delta Z, \delta\theta)$, in which δZ and δX has been calculated as:

$$\delta Z = 2Z_c sin(\delta\theta/2) \quad \& \quad \delta X = 2Z_c cos(\delta\theta/2)$$

This compensates the effect of the deviation of the base of the manipulator. Nonetheless, the manipulator may not yet have the desired pose for gripping. This is due to the general robotic arms error sources which have already been described (Type A Error).

B. 3^{rd} Phase of Each Step: Compensation of Type A Error

For precise positioning of the gripper, this error should also be compensated. For perfect gripping, the manipulator should be perpendicular to the structure and at a certain distance from the structure. This assures that the system will not be over defined after gripping. Therefore, in the 3^{rd} phase of each step, the absolute angle of the manipulator and the distance of the manipulator from the structure will be measured and the relative error will be compensated.

C. The Proposed Algorithm

Figure 4 shows the simplified version of the algorithm for making one step composed of three phases. In this algorithm, to calculate the current task space position of the manipulator relative to the base, links' angels are measured by accelerometers and the relative angle between them are calculated $(\theta_1, \theta_2$ and $\theta_3)$. Finally, through the direct kinematics formulation, the current position of the manipulator is calculated. In this way, as the $(\theta_1, \theta_2$ and $\theta_3)$ are measured through inclinometers, they provide an external feedback

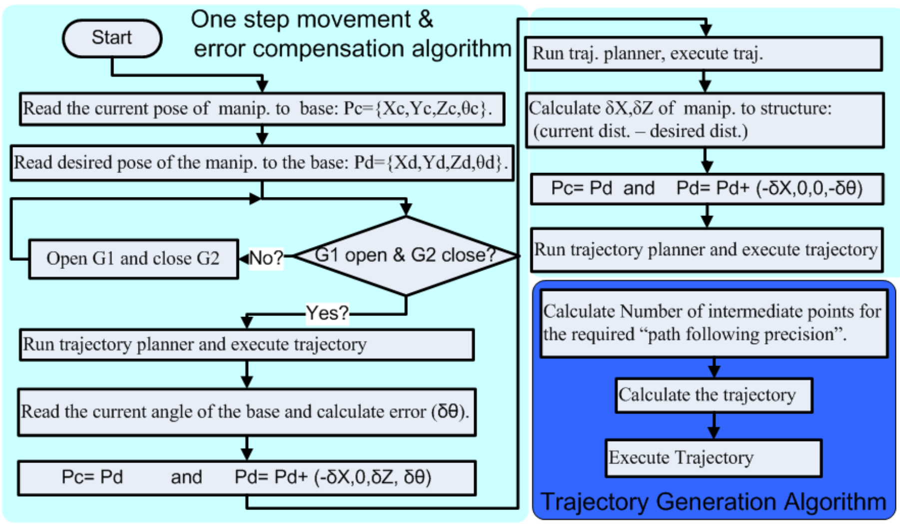

Fig. 4. Self calibration algorithm

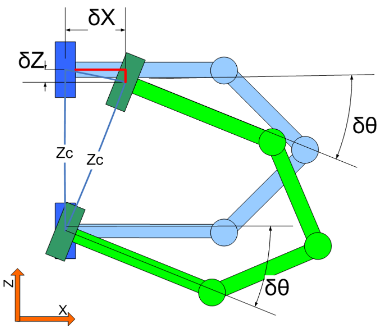

Fig. 5. The error on the placement of the base generates a relative error on the manipulator

to (θ_1, θ_2 and θ_3) which are measured by encoders. Inclinometers serve to address the problem of fine manipulation of large manipulators because they are installed directly on the arm and does not contain errors related to gearing backlash, coupling mechanism and improper placement of the base. Inclinometers also provide very useful information, when the robot is moving through bent sections, where the absolute inclination of the manipulator should be known. Figure 6 shows the status of the robot before execution of the step, after execution of the step and after compensation of the error (Only the first and the second phases are shown here). The question might be asked that why two phases of error compensation are required. The answer is that it is possible to avoid the second phase of each step. In this case, the manipulator can be placed in a specific pose in which the gripper can precisely grasp the structure. However, an important difference between phase 2 and phase 3 of each step should be noticed. The second phase is associated with larger errors caused by the deviation angle of the base. This deviation causes relatively large errors ($\delta X, \delta Z$ and $\delta\theta$) of the manipulator. The second phase of the steps compensates all of these errors. If, due to any other source of error including what has been introduced as Type A, the manipulator is not in the appropriate pose for gripping, then the third phase of the algorithm only compensates (δX and $\delta\theta$) in order to effectively grasp the structure. The difference is that the second phase tries to place the manipulator in the desired pose as much as possible, while the third phase tries to place the manipulator in the precise gripping position even if the manipulator's pose differs from the desired pose. Therefore, if the second phase is avoided, the robot can still grasp the structure, but the Z element of the manipulator will noticeably differ from the desired Z.

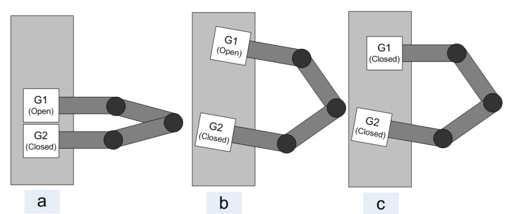

Fig. 6. Autonomous self calibration illustration

Algorithm 1: Trajectory generation algorithm

Read$\theta_1, \theta_2, \theta_3$ from inclinometers
$P_c \leftarrow$ Calculate current Pose using direct kinematics
$P_d \leftarrow$ Read the The desired Pose
$\delta_{max} \leftarrow$ Read the maximum possible deviation from the path
$n \leftarrow 0$, $\delta \leftarrow C$ (Constant big enough value) **while** $\delta > \delta_{max}$ **do**
  $n = n+1$;
  Calculate n points between P_c and P_d
  $\delta \leftarrow$ Calculate the error on the path based on n points
Calculate the trajectory based on n points using inverse kinematics
Execute the trajectory
End of algorithm

V. Sensors

As stated, distance and angle measurement sensors are necessary for the execution of the proposed algorithm.

A. Range Finders

The distance between the pole and the structure is measured using range finders (Figure 7). Sharp GP2Y0A21 range finder can measure from 10 *cm* to 80 *cm* (Figure 8) and is used for estimating the distance between the manipulator and the structure. Figure 9 shows the graph of "distance to the reflective object" for a gray paper and a white paper against the output "voltage" of the sensor extracted from

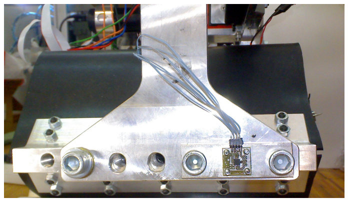

Fig. 11. The inclinometer board installed on the upper link

the data sheet. The data sheet of the sensor do not provide more information about the sensitivity and repeatability of the sensor. Therefore we investigated some other aspects with experiments. According to our experiments, the color change may cause a maximum of 5 *mm* error in distance measurement but can be easily calibrated with an offset value. As it can be seen in figure 7, the pole surface is not flat and therefore the output voltage could be different from the flat surface. This was also tested. This error depends on the radius of the circular profile. Consequently a compensation function was developed which receives the radius of the profile as input and corrects the distance according to that. Finally, as it can be seen from the graph (Figure 9), the sensor is more sensitive in the closer ranges. To increase the resolution, the range finder were placed as near as possible to the structure (In the distance of $60mm$ from the structure, when the gripper is closed). As an example, our experiments showed that in the distance of $200mm$ the sensitivity of the sensor is 8 mV/mm. Using the 14 bit data acquisition and considering a $1mV$ resolution of voltage acquisition, a resolution of 0.2 *mm* can be easily obtained. However the accuracy of the measurement is only limited by the accuracy of the calibration method for the specific color and radius.

B. Inclinometers instrumentation and calibration

Four accelerometers are necessary for absolute inclination measurement of all links including base and manipulator of the robot. Any change on the angle of each link, cause a change on the effect of the gravity acceleration on each axis and thus changes the output voltage of the accelerometers. Measuring absolute inclination of all links and using the direct kinematics formulation, the current task space position of the manipulator relative to the base can be calculated. Moreover, by installing an inclinometer on the base, the deviation of the robot's base angle from the desired angle can be measured. Additionally, as the robot should climb from bent sections, inclinometers can provide useful data about the current angle of the manipulator for grasping a $45°$ or $90°$ bent section. In order to do that, a STMicroelectronics ultra compact LIS244AL two-axis analogue accelerometer chip is used. This chip is integrated in a board (Figure 10) and installed on the robot grippers and links (Figure 11). This sensor has two analogue outputs for X and Y axes. The output voltage is read through a National Instrument data acquisition. The value is then compared with a pre-filled data table, in which "X" and "Y" axes voltages are assigned to each angle in range of $0° - 180°$ with $0.3°$ steps.

1) Sensitivity: The sensitivity of accelerometers on each axis varies between $0.2mV$ to $6mV$ per degree. However, each axis is more sensitive in a specific range of values and less sensitive in other ranges. For instance, sensitivity of Y axis in range of $45° - 135°$ degrees varies between $3mV$ to $6mV$ /degree. Consequently, considering each axis on its more sensitive domain, a sensitivity of $3mV$ to 6 mV per degree is possible.

Figure 12 shows the measurement of signal on Y axis, while the angle is 40 degrees in 4 seconds. The signal ranges from $1.209mV$ to $1.226mV$ which have a difference of $17mV$ (considering the $4mV$ per degree the error on angle estimation might be up to $4°$).

2) Fault Tolerance and Filtering of Mechanical Vibrations: For an effective calibration of the system, a precision of about $0.5°$ is required. It should also be mentioned that, in practice, the 3DCLIMBER robot always has vibrations due to spring characteristics of the links. Vibrations change the output voltage of the accelerometers due to the acceleration. It also adds some acceleration to the links which affects the output value of the accelerometers. The only positive aspect is that these vibrations are low frequency and mostly under $10Hz$. Therefore, a method which averages sufficient samples acquired at high frequency was applied. If the sampling frequency is adequately greater than the mechanical vibration frequency and if a large enough number of samples gets acquired and averaged, the low frequency vibrations will be eliminated. With some experiments, we found the average value of 200 to 400 samples (total time of 2-4 seconds) acquired at the rate of $100Hz$ (10 times larger than the mechanical vibrations' frequency of the links) is very reliable, as it has good repeatability and can filter the effect of the mechanical vibrations. It showed a repeatability precision of $0.07°$ $(4')$. To test the repeatability against the mechanical vibrations effect, the plate on which the sensor was installed, was manually vibrated with different frequency and amplitude similar to what happens with the 3DCLIMBER. This is shown in figure 13 and 14, i.e. the average value did not change more than $0.1mV$ even with existence of vibrations with $6Hz$ frequency. The average value in a relatively high amplitude vibration (Figure 15) has only changed about 1 mV. This provides us with a precision better than $0.3°$ $(20')$ even with existence of relatively high amplitude vibrations. Characteristics of the developed inclinometers are summarized in Table I.

VI. Results

The proposed calibration method has been applied after each movement step and just before grasping the structure. Analog accelerometer sensors were installed on the base and the manipulator of the robot. The analogue outputs of X and Y axes were transferred to a 14 bit National Instrument data acquisition, and the angle of the base and manipulator were estimated with a precision of $20'$. This precision is valid even with the existence of vibrations up to 10 Hz during operation of the 3DCLIMBER (results of analysis is shown in Figures 12 to 15). To attain such precision, the

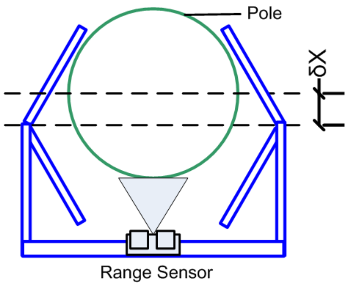

Fig. 7. Schematic of the gripper distance error compensation

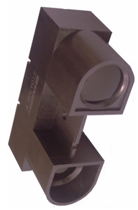

Fig. 8. Sharp range finder

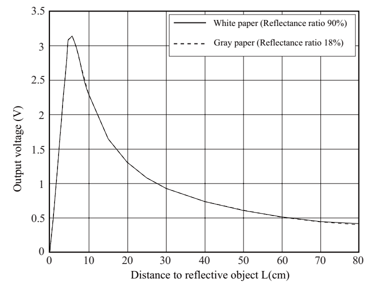

Fig. 9. The output "voltage" of the Sharp sensor against the"distance to a gray & a white paper"

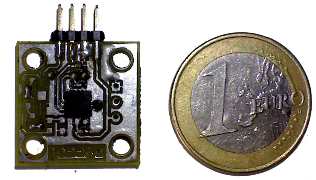

Fig. 10. The accelerometer board developed at ISR

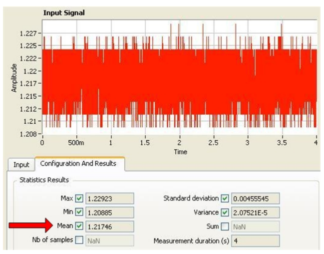

Fig. 12. Y axis values of the accelerometer at 40°

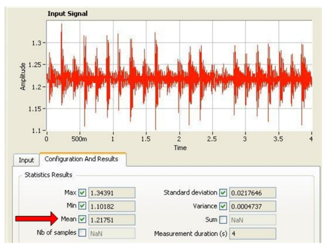

Fig. 13. Y axis values @ 40° & 6Hz normal amplitude vibration

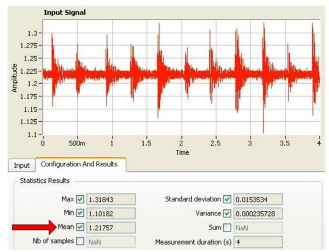

Fig. 14. Y axis values @ 40° & 3Hz normal amplitude vibration

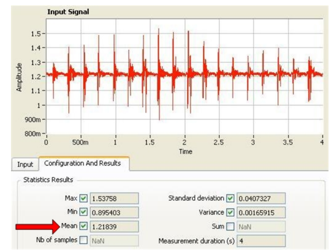

Fig. 15. Y axis values @ 40° & 5Hz wide amplitude vibration

Sensitivity	From $\frac{3mV}{1^\circ}$ to $\frac{6mV}{1^\circ}$
Repeatability based on one sample	4°
Repeatability based on average of 400 samples at $100Hz$	0.07°
Repeatability based on average of 400 samples at $100Hz$ and existence of $5Hz$ mechanical vibrations	0.2°

TABLE I

CHARACTERISTICS OF THE INCLINOMETER SENSORS WITH STM LIS244AL 2 AXES ACCELEROMETER CHIP

average value of 200 to 400 samples was calculated. To filter the effects of the mechanical vibrations of the links during operation of the 3DCLIMBER on the estimated angle, the sampling rate was set up at 100 Hz (10 times larger than the estimated frequency of the mechanical vibrations of the links). Using two sharp range finders, the distance between the manipulator and the structure was also estimated. Before integration of the sensors and the proposed algorithm, the base of the robot had an angular deviation of $1-8^\circ$. The same angle error was transferring to the manipulator, as the manipulator movement is relative to the base movement. Moreover, X and Z of the manipulator related to the base of the robot had errors relative to the deviation angle of the base. These errors were adding to the other sources of errors e.g. deflection of the links. Consequently, the gripper of the robot was not positioned correctly before gripping, adding extra constraint to the robot and leaving the system over defined. Considering that the gripper has a mechanically self centering feature (due to V shaped end effectors), even if the gripper succeeded in grasping the structure in the existence of errors, it would cause an error in the position of the manipulator of the 3DCLIMBER. The reason for this is that the gripper was forcing the manipulator to move to a new position which was not set by the user. Consequently, the climbing mechanism motors were pulling maximum current to compensate the error. Not only was this likely to damage motors, but the error was accumulative and reached a level where the operator had to stop the robot and calibrate it manually. Taking advantage of the self calibrating algorithm, the manipulator position was corrected in 2 steps. In the first step, the positioning errors of the manipulator related to the base were compensated. In the next step, the pose of the manipulator's gripper relative to the structure was set in a constant specific pose, so that all coupling errors, gear backlashes and deflection of links were compensated. In this way the angular deviation of the manipulator was reduced from 1° to 1° in the worst case and it was not accumulating at each step. The robot was able to make as many steps as desired by the operator, without any need for manual calibration. The positioning error of the manipulator on the Z direction was improved from $48mm$ to $6.1mm$ (values in the worst case, based on the maximum measured positioning error of the base). The worst case value was measured on the edges of the manipulator's workspace, where maximum torques are applied to the base of the robot and geometrical parameters which are multiplied by the angular deviations are at their maximum. In most of the robot's workspace an accuracy of 3 mm was easily obtained. Table II shows some of the improvements on the robot performance after integration of self calibration algorithms and sensors.

	Before	After
Angular error on placing the gripper on the structure	$1° - 8°$	$1°$
Positioning error type	Accumulative	Reset @ each step
Maximum positioning error of the manipulator in the worst case	$48mm$	$6.1mm$

TABLE II
IMPROVEMENTS ON THE ROBOT'S PERFORMANCE AFTER INTEGRATION OF SELF CALIBRATION ALGORITHMS AND SENSORS

VII. CONCLUSIONS

This paper introduced a calibration and error compensation method for precise positioning of grippers in step-by-step based climbing robots. In addition to all well known problems in fine positioning of large manipulators, the base of the climbing robot is not fixed and also deals with positioning problems. An inclinometer which is tolerant to mechanical vibration has been developed to act as an additional feedback for compensation of positioning errors. Using an infrared range finder along with the developed inclinometer, the positioning error of the manipulator was reduced from $48mm$ to $6.1mm$ in the worst case. The robot was tested on the structure and was able to make as many steps as desired by the operator, without any need for manual calibration. The same method and sensors can be used for other step-by-step based climbing robots with only the kinematics formulation differing.

VIII. ACKNOWLEDGMENT

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