Surface Operation Requirements for the ExoMars Rover Vehicle Instrument Deployment Arm (IDA)

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Surface Operation Requirements for the ExoMars Rover Vehicle Instrument Deployment Arm

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INTRODUCTION

The Aberystwyth University (AU) Space Robotics Research Group has undertaken a Phase B1 study into the key instrument deployment requirements for the ESA ExoMars rover vehicle Instrument Deployment Arm (IDA). These requirements include the IDA's working envelope, positional and angular repeatability and accuracy, instrument positioning and re-positioning, and the ability to deploy an instrument without requiring a further iteration cycle from ground control. A preliminary baseline design for the ExoMars IDA is the Beagle 2 (B2) arm, and the AU study has made extensive use of the B2 Development Model (DM) arm [1], which has been on loan from EADS Astrium. The study was carried out at the AU Planetary Analogue Terrain Laboratory (PATLab).

BEAGLE 2 HERITAGE

The study presented here draws on previous work that was undertaken by AU for the ESA Mars Express mission and Beagle 2 [1]. We were responsible for creating a 3D simulation of Beagle 2 that was to be used during the mission for training, rehearsals and commanding the Beagle 2 arm during surface operations. Beagle 2 Catia format CAD data was obtained from EADS Astrium and imported into a robot simulation software package (Envision). This allowed a complete virtual Beagle 2 lander to be built which could be used to rehearse potential mission arm configurations and instrument deployments. To ensure that the virtual model was a faithful representation of the real Beagle 2 on the Martian surface, including the arm kinematics, a detailed arm calibration campaign was required. The calibration work was undertaken by us at EADS Astrium, and forms the background to the ExoMars IDA study presented here. Many of the procedures originally developed for the Beagle 2 calibration campaign were repeated for this study.

EXOMARS IDA STUDY REQUIREMENTS AND REPORT

The IDA requirements that this study addresses were taken from ESA document EXM-RM-SSS-AI-0014, section 4.3.9, pages 111 & 112. Requirements include targets for positional repeatability & accuracy, angular accuracy and arm working envelope, and specific instrument deployment goals. The work described here was was reported in detail in [2].

ARM CONTROL STRATEGY

The arm control strategy for the Beagle 2 mission did not incorporate any motor speed control, neither was it possible to drive more then one motor at any given time. All arm end-effector (PAW instrument) positioning had to be achieved using only joint-by-joint control. This strategy was appropriate for the single and restricted working area anticipated for the B2 lander. ExoMars, on the other hand, has much more ambitious science demands for accurate instrument placement and precise motion trajectories (e.g. for the CLUPI instrument). These can only be met if an arm motion control strategy capable of following a specified trajectory is available. Such control means that it is essential to be able to move more than one joint motor at once, and to vary the speed of each motor independently.

EXOMARS BEAGLE 2 ARM STUDY SETUP

PATLab

The Planetary Analogue Terrain Laboratory (PATLab) at AU provides a flexible test environment for planetary surface operations including rover mobility, science target selection and analysis, and instrument deployment. The PATLab includes a region of simulated Martian terrain in which Mars Soil Simulant-D is used to provide realistic wheel traction and digging mechanics. A collection of rocks of known geological characteristics is available for use as experimental science targets.

The Martian terrain area is instrumented by two separate measuring systems. The Vicon tracking system uses a set of 12 specialised infra-red cameras to track reflective markers within the terrain with an accuracy of around 0.1 mm. These markers can be placed on any object - such as a robotic arm - to enable recording of position and orientation at up to 120 frames per second. Complementing the spot-measurement of the Vicon tracking system is a Leica Geosystems 3D laser scanner. This device allows the entire terrain surface to be mapped in three dimensions with a high sample density, providing "ground truth" digital elevation model (DEM) measurements for comparison with DEMs generated by stereo imaging or other techniques under investigation.

Calibration and Test Rig

The Vicon system calibration procedure requires identifying a master reference frame, which takes the form of a precise arrangement of four reflective markers mounted on a machined base (the "L-Frame"). Once calibrated, the coordinate system for subsequent measurements is locked to this reference frame. During the original Beagle 2 arm calibration work, a separate L-Frame was placed within the working area and the relative position and orientation of the arm base measured using a theodolite. This process was time-consuming and vulnerable to errors should the L-Frame be accidentally displaced.

To avoid any displacement problems during the ExoMars IDA study, the required L-Frame was incorporated as part of the basic arm mounting structure. The resultant calibration rig is shown in Fig.1, with the arm mounted in the horizontal (Beagle 2) configuration. The four Vicon markers constituting the integrated L-Frame are indicated along with the origin and orientation of the coordinate system defined by them. An additional support structure raised the calibration rig to the correct height above nominal ground as specified in the Phase B1 rover and arm design.

Simulation Environment

CAD data for the calibration rig was received from EADS Astrium and imported into the Aberystwyth arm simulation software environment along with coordinate frames, Vicon markers and a representation of the Beagle 2 arm. Two simulation workcells were created. One had the arm mounted on the horizontal calibration rig plate with the joint 1 rotational axis vertical - the "Beagle 2" mount configuration (see Fig. 2).

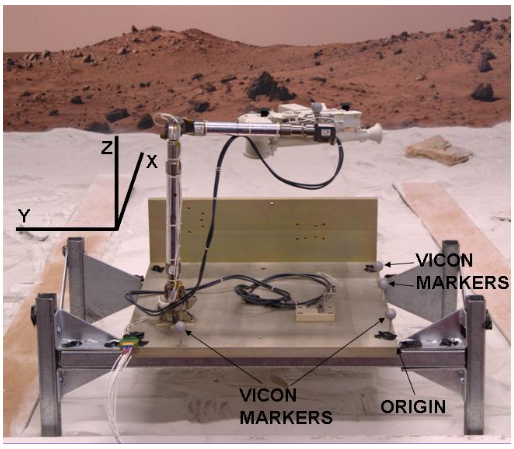

Fig. 1. ExoMars IDA study calibration rig

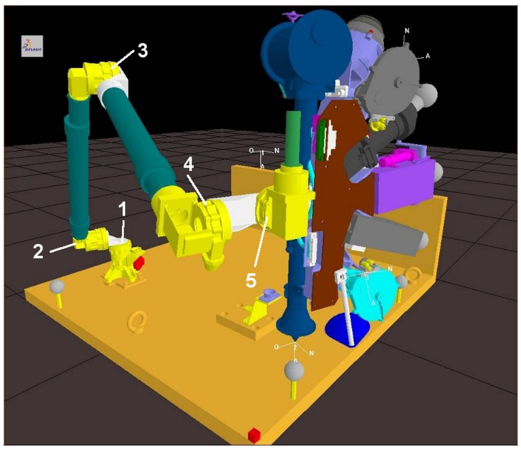

Fig. 2. Virtual calibration rig (joints marked)

The second workcell had the arm mounted on the front vertical calibration rig plate with the joint 1 rotational axis horizontal - the“ExoMars Phase B1” mount configuration. The forward and inverse kinematic models and joint-offset data generated from the Beagle 2 calibration work were used throughout the study to generate joint angle data for the experiments undertaken. Both arm mount configurations were used with the real arm during different parts of the study.

Measurement and Control Hardware

The Beagle 2 DM arm as supplied by EADS Astrium included “H-bridge” power driver circuitry with a parallel interface and a switch box for manual control. Additional hardware and software was designed to allow precision automatic control and measurement of the arm during testing.

Control PC and Interface

A standard desktop PC running the Linux operating system was used for all laboratory tests. Unnecessary system services and events were disabled to avoid any possible disruption to the arm control application. The interface card used to control the arm was an EDRE EagleDAQ PCI730 combined A-D/D-A and digital I/O board. This card provides 16 channels of 14-bit A-D conversion (up to 100,000 samples/sec) and 3 × 8-bit digital I/O ports. The digital I/O ports were used to communicate with either the basic power driver or a dedicated motor speed control board (see below). The analogue inputs were used to monitor arm joint angle potentiometer voltages and their associated reference voltage.

PWM Speed Controller

The basic arm driver circuitry only provided bi-directional, full-speed control of the arm joint motors. In order to allow precise control of arm joint motor speeds, a multi-output pulse-width modulation (PWM) control board was designed and implemented. A dedicated microcontroller (PIC18 series) was used to ensure reliable waveform generation without disturbance from the host PC's devices or operating system. The PWM speed controller board has a simple and fast parallel interface using 11 data and 2 handshaking lines, and is capable of driving all five arm joint motors simultaneously with a base PWM frequency of 500 Hz. There are 128 forwards and backwards speeds available including “stop”. A number of controller configuration commands are also supported.

Arm Control Software

A comprehensive test suite application has been developed which allows both interactive and automated control of the arm and measurement systems. The software implements a command language that encompasses the definition of target positions and movement sequences, execution of movements in joint-by-joint, simultaneous-full-speed and joint interpolated motion modes, examination of joint angle positions, communication with the Vicon system to obtain accurate 3D position information, time-series filtering of potentiometer and reference voltage values, and flexible logging and debugging commands. The software can be driven from a script file, and script files can be invoked interactively to define a test environment, or to run a particular test automatically. The software can take advantage of full speed control as supported by the hardware PWM board, or it can be configured to use the basic power driver interface directly, without speed control.

EXPERIMENTS

Arm Envelope

To visualise and measure the arm work envelope in the context of the ExoMars Phase B1 rover design, simulation work was performed using the arm in the vertical (ExoMars) mount configuration. The Beagle 2 arm joint range values were used throughout. A virtual Mars ground object was placed within the arm envelope simulation model at an appropriate height. Semi-transparent wire-frame arm envelope objects were generated using the arm kinematics model with the Mössbauer instrument on the PAW taken as the kinematics end-point.

The arm envelope algorithm uses the first three joints of the arm kinematics model together with an additional translation offset to account for the Mössbauer instrument end-point. The envelope objects thus generated can be visualised together with the simulated calibration rig and arm and suitable measurements taken. Figs. 3a & 3b show the reachability volume of the arm for the given instrument end-point. The approximately spherical envelope objects show how close to the arm base an instrument can be placed as well as the reach of the arm when fully extended.

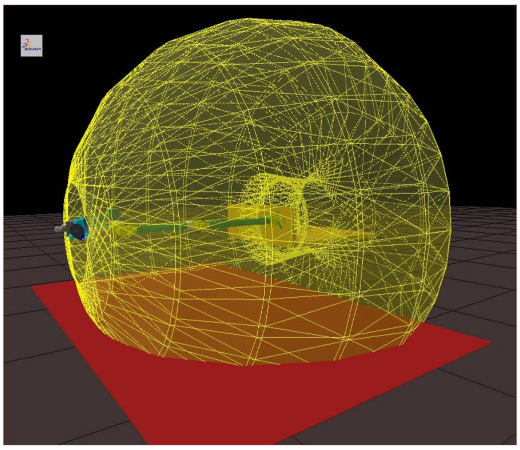

Fig. 3a. Arm reachability envelope (above)

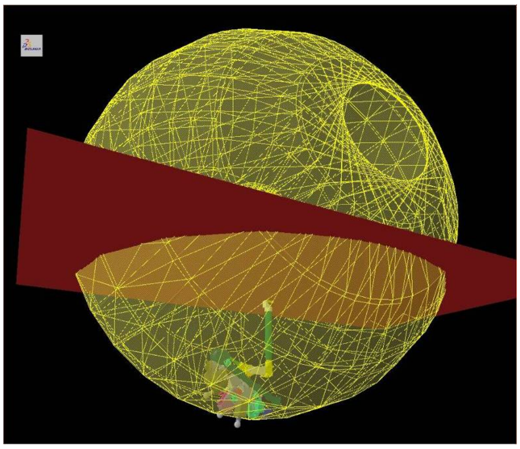

Fig. 3b. Arm reachability envelope (below)

Joint Motor Control and Overshoot

For the ExoMars instrument arm deployment study, it was decided initially to re-implement the Beagle 2 strategy of moving a joint at a given motor speed until the target angle was reached and then simply stopping the motor ("bang-bang" control). However, we knew that this would result in some joint angle overshoot partly due to the time it would take to decelerate the motor once commanded to stop and partly due to backlash and play in the joint gears. The latter is particularly relevant to the PAW joints (4 & 5) which were known from B2 work to have a significant amount of backlash. Whilst this overshoot would not impact on the proposed arm repeatability experiments (whose measurements would be relative to one another), it would affect the proposed arm accuracy experiments, where the measurements would be absolute with respect to the Vicon measurement system origin.

To investigate the extent of joint overshoot when the motors were suddenly stopped, joint potentiometer voltage data was gathered while the joints were being moved individually over a small range of angles in either direction. Samples were captured at approximately 4800 Hz (the average control loop repeat rate) for 0.5 s before and after the point at which a motor was stopped. After allowing time for joint settling, a precise final angle reading was taken. The resulting data was plotted to show the arm dynamics in joint space at the end of a movement. Typical plots for joints 3 and 5 are shown in Figs. 4a and 4b. The blue dashed lines indicate the target angle and the time at which the motor was stopped. The solid red line gives the continuously-measured joint angle, while the dashed red line marks the final steady-state joint angle as measured accurately after settling.

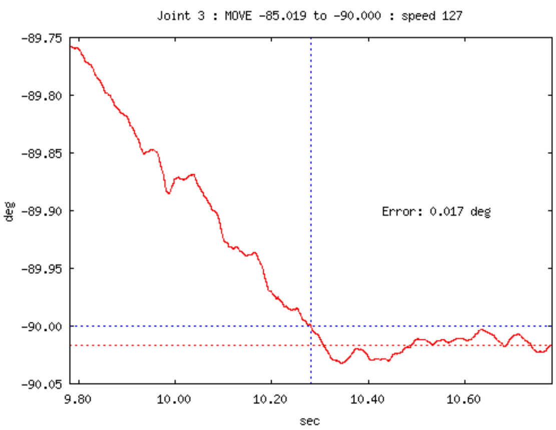

Fig. 4a. Joint 3 overshoot

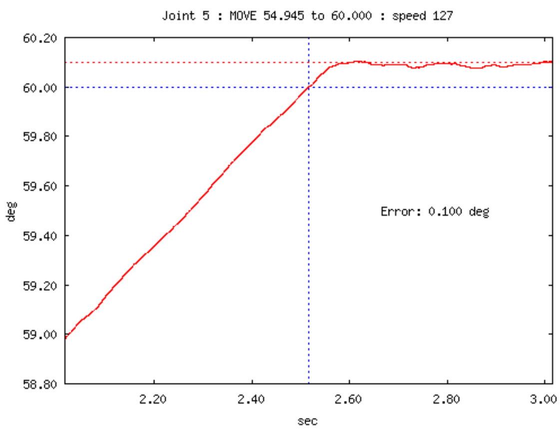

Fig. 4b. Joint 5 overshoot

The largest error observed was around 0.1 degrees, which is in agreement with the error observed during the original B2 arm calibration work [1]. Some oscillatory behaviour can be seen, particularly for joints 2 and 3 which are supporting the longest links. One possibility to minimise oscillation and overshoot would be to improve the adopted control method, for example by using a trapezoidal velocity profile as employed by the NASA MER mission [3]. This would reduce the magnitude of the impulse applied to the arm links and hence reduce oscillation and overshoot. A more sophisticated feedback control strategy such as a proportional-integral (PI) or even a full proportional-integral-differential (PID) controller could also be used. However, with the relatively low maximum joint velocities of the B2 arm, it is not clear whether this would give an advantage over the simpler trapezoidal speed control. Investigation of these alternate joint control methods was beyond the scope of this study.

Positional Repeatability

For the ExoMars IDA study, the same repeatability procedure was used as designed for Beagle 2 [1]. The arm simulator was used to generate joint data for the positional repeatability experiments. A goal point was first created, followed by a representative sample of 8 different starting points within the workcell with the arm joints moved by 20 degrees away from the goal point in various directions. The arm was then moved from each starting point in turn to the goal point. Movement was joint-by-joint at full motor speed - no speed control was used in these tests. Each time the arm returned to the goal position the position of the Mössbauer instrument marker was measured using the Vicon tracking system.

The repeatability experiment was run 3 times. The calculated measure of positional repeatability was the radius of a sphere large enough to just enclose the measured goal point positions. Results were: 0.544 mm ±0.058 (test 1), 0.299 mm ±0.031 (test 2) and 0.498 mm ±0.027 (test 3). The 1σ error bounds are derived from the Vicon tracking system data. The result for test 1 is greater than the ExoMars IDA requirement of 0.5mm radius, but the results from the other runs are within the specified limit. A major contributor to the repeatability error is thought to be the previously-mentioned joint 4 & 5 backlash.

Positional Accuracy

To test positional accuracy, a known and reachable point in the workcell - one of the Vicon calibration markers - was chosen as a target for the Mole instrument tip. The B2 arm simulator was used to calculate the arm joint configuration required to place the Mole instrument tip a specified distance above the marker position. This set of joint angles was then applied to the real arm, and the actual arm position achieved measured using the Vicon system.

The inverse kinematics model available for joint angle calculation was that produced for Beagle 2. This model relies on knowing the position and orientation of the intended work area relative to the B2 lander, i.e., the region of interest in which the PAW is working. The closest equivalent area of the B2 lander corresponding to the position of the Vicon target marker on the test rig was the calibration target plate (250 mm Euclidean dist). However, it was never planned for the Mole to visit the calibration target plate during the Beagle 2 mission, hence no kinematics-joint-offset data was generated for the Mole in this region. The only other 'close' region to the Mole when in the accuracy experiment goal configuration was the Gas Analysis Package (GAP) region, hence this kinematics-joint-offset data was used. However it should be noted that when in the accuracy experiment goal configuration the Mole to GAP Euclidean distance is about 350 mm. This will have affected the achievable positional accuracy.

Once the arm had been moved into the goal joint configuration, the final position of the PAW was measured using the Vicon system. The Mössbauer marker was used for this measurement because the Vicon system found it difficult to differentiate the Mole marker from the L-Frame marker as the arm approached its goal target. To avoid this problem, the Mole marker was removed temporarily. The predicted position of the Mössbauer instrument tip was compared to its actual position as a substitute for measuring the Mole tip directly. The Mole tip position was also checked visually.

The measured positional accuracy (Euclidean distance error) from this test was 7.515 mm ±0.012. This is better than the required 1 cm Euclidean distance accuracy, despite the kinematic model not being optimised for this scenario.

Straight Line Trajectory Control

To conduct the straight line trajectory experiments, joint configuration data was generated using the arm simulator. The target instrument was chosen to be the Mole and straight line arm trajectory joint angles were generated for trajectories in each of the x, y and z directions. As with the positional accuracy tests, the Beagle 2 GAP region kinematics offset model was used. Based upon the work of Taylor [4] intermediate *knot points* along each trajectory were created and the corresponding joint angles calculated and applied to the real arm. Whilst the arm was moving along each trajectory, the 3D position and orientation of the Mole instrument tip was recorded using the Vicon system. Three different techniques for following the trajectories were investigated: Joint-by-Joint (JBJ), Simultaneous Full Speed (SFS), commonly referred to as 'Slew Motion', and Joint Interpolated Motion (JIM).

Joint by Joint (JBJ) Motion

In this kind of arm movement, the joints were moved individually in sequence, at full speed. A fixed joint order was used: 5-4-1-3-2, which was the normal mode of operation for the Beagle 2 mission. It has the benefit of simplicity of commanding and low power consumption, as only one motor moves at a time. However it is slow, and instruments may be moved through large arcs in different planes while moving to their destination.

Simultaneous Full Speed (SFS or Slew Motion)

With this type of arm movement, all five joints were started simultaneously at full speed. Each joint was stopped when it reached its target angle. This mode was considerably faster than joint-by-joint movement, and for most movements resulted in a more obviously direct trajectory, though it was seldom a good approximation to a straight line.

Joint Interpolated Motion (JIM)

For JIM mode, a separate motor speed was computed for each joint, based on the time it would take for the slowest joint to complete its movement. All joints were started simultaneously, and each was stopped when it reached its target angle, as for the SFS case. The speed for a given joint was not changed during the movement with the simple algorithm used in these tests.

The theory of JIM mode is that a linear trajectory in Cartesian space is approximated by a series of short linear trajectories in joint angle space. As long as several intermediate points along the trajectory are pre-computed and the arm is moving in a 'good' calibration data region of its working envelope (and not near any singularities), this strategy can result in smoother motion than the other two methods. It does, however, require speed motor control to be available, and this must be calibrated for best results. It was not possible during the testing period to acquire sufficient motor speed data to produce an accurately calibrated speed model. In place of an accurate model, an approximate maximum speed was calculated for each joint from data logged during test runs. This gave reasonable results but was inaccurate in some configurations.

Figs. 5a & 5b compare representative straight-line trajectories for slew motion and joint interpolated motion. The side-view (Y-Z) plots show the trajectory followed and both the commanded and measured knot points for straight-line movement along the Vicon negative Y-direction.

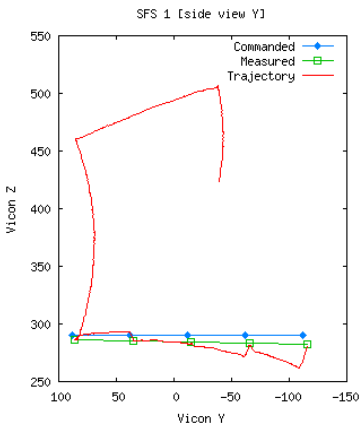

Fig 5a. Slew motion trajectory

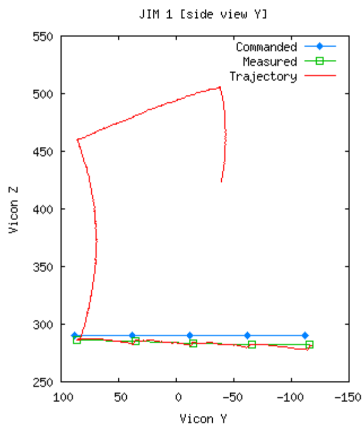

Fig 5a. Joint-interpolated motion trajectory

The smoothness of the trajectory (approximation to a straight line) is clearly better for JIM than for slew motion. The errors in slew motion are particularly noticeable as each knot point is reached, when one joint finishes moving before the others. Both types of trajectory also show a gradual drop in measured position relative to the commanded position. This is largely due to arm deflection at greater extension, and reflects the fact that the GAP region kinematics model used only partly fits the actual arm working area. The development of a combined kinematic and arm deflection model for the proposed ExoMars IDA would improve the accuracy of straight-line motion by enabling more accurate inverse kinematics and also by allowing more realistic joint speeds to be estimated for use in JIM calculations.

Angular Repeatability and Accuracy

A measure of the instrument angular repositioning accuracy and absolute instrument angular accuracy was obtained by tracking Vicon markers on the top of the PAW and on the instrument tips while performing simulated instrument deployment using a straight line trajectory (JIM control). From these measurements the relevant pitch and yaw angles were calculated during the motion. Although the markers were not aligned along the PAW instrument axes, the angular variation of the calculated vectors during instrument deployment provided an indication of the accuracy with which the approach orientation was maintained.

The vector between the PAW top marker and the appropriate instrument marker (e.g. Mole, RCG and Mössbauer) was calculated at three positions (tag points) along a straight line trajectory. These vectors were then compared against the 'as commanded' vectors which were derived from the relevant markers modelled within the arm simulation environment. The experiment was run twice, and the results for each instrument compared.

Our study found that the best case approach direction angular accuracy was 0.681degrees (half cone angle: derived from minimum error in pitch for the Mole instrument), and the worst case approach direction angular accuracy was found to be 4.459 degrees (half cone angle: derived from max. variation in pitch for the Rock Corer-Grinder instrument). Neither of these results falls within the required 0.5 degree half cone angle.

The worst case error is far greater than the required approach direction accuracy of 0.5 degrees half cone angle. However, there are several points to note in mitigation. Firstly, a straight line trajectory capability is vital for achieving any approach direction accuracy. Secondly, well calibrated potentiometer-joint-offset and kinematics-joint-offset models are essential to achieve a high approach direction accuracy and positional accuracy. Thirdly, for the straight line trajectory control algorithm used (JIM) we need a good estimate of the maximum joint speeds for all arm configurations involved in the test. Finally, any backlash errors in joints 4 and 5 must be negligible - which was not the case during the study. Some of the detailed measurements showed consistent errors that were clearly related to PAW orientation.

Instrument Deployment

Having completed the arm repeatability, accuracy and straight-line motion experiments, it was decided to investigate three instrument deployment scenarios. The first scenario was for the Close-Up Imager (CLUPI) instrument, and the second and third were for a generic instrument swapping activity. For the third scenario, the arm was mounted on to the calibration rig in the vertical (ExoMars) configuration.

Simulated CLUPI Deployment

We performed a simulation of a CLUPI Mode III operation, using the Mössbauer instrument to represent CLUPI and the Mole instrument to represent a "brushing" tool. This involved advancing the instrument in 3 × 2 mm increments; performing a "brush" activity with another instrument then restoring the CLUPI position; retreating in 3 × 2 mm increments; moving sideways by 10 mm and finally repeating the 3 × 2 mm increment advance. Joint angles for the trajectories were calculated using the arm simulator and applied to the real arm using the joint-interpolated motion control strategy. The position of the CLUPI (Mössbauer) instrument point was measured at each point using the Vicon system.

Results from one run are shown in Figs. 6A & 6b. Fig. 6a shows excellent correspondence to the desired accuracy along the CLUPI Z-axis (Vicon Y). The positional increments are close to 2 mm and the repositioning after "brushing" is to within 0.5 mm. Fig. 6b shows the displacement along the CLUPI Y-axis (Vicon X). Clearly the arm is having trouble maintaining an accurate angular instrument yaw (joint 5), whilst performing the 2 mm forwards and reverse. The 10 mm 'sideways' displacement needs to be improved upon also.

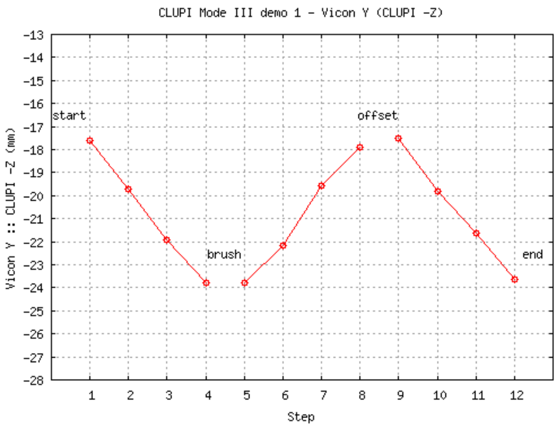

Fig. 6a. CLUPI deployment (Z-axis)

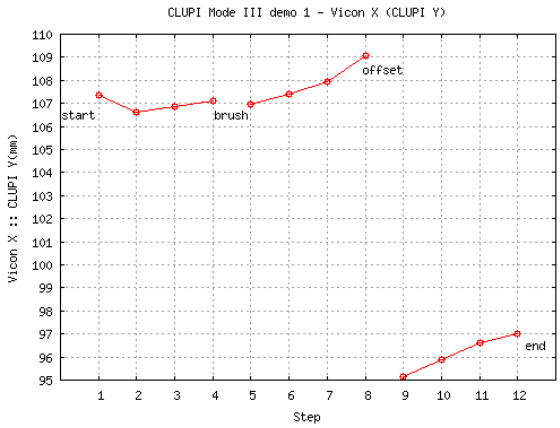

Fig. 6a. CLUPI deployment (Y-axis)

The error in the Vicon Z-axis motion (not shown here) is less than 1 mm. Given the amount of backlash in joints 4 & 5, we are encouraged by these results. There is plenty of scope for improvement in the arm's joint 4 & 5 mechanics, and together with improvements that can be made to our joint interpolated motion control method, we believe that it should be possible to deliver the high arm motion precision called for when capturing CLUPI image data.

Simulated Instrument Deployment

Three of the PAW instruments in succession were moved along the same straight-line horizontal trajectory. The measured instrument marker positions were used as data for calculating angular repeatability and accuracy values. A further test involved a full arm deployment sequence from the ExoMars stowed position to a pre-determined target, "sampling" of the target in the same place by two different instruments, and re-stowing of the arm. Measurements were taken and a video of this "simulated science" run was recorded for further study.

CONCLUSIONS AND RECOMMENDATIONS

This study has led us to conclude that whilst there is room for improvement to the Beagle 2 arm, we have found no 'show-stoppers'. On the contrary, in many cases only relatively minor improvements would be necessary to equip the arm for the rigours of the ExoMars mission. We make a number of recommendations for further arm development, including the following (a complete list of our conclusions and recommendations can be found in [2]):

- Simultaneous joint speed control is essential for straight-line trajectory motion.
- A combined arm kinematics and deflection model should be developed to support accurate placement and trajectory following in all regions of the arm's working envelope.
- All backlash in the arm joints should be removed.
- Arm movement should be controlled by a dedicated arm controller with tight coupling between position feedback and motor control.
- Fiducial markers should be machined on to arm parts to allow key configurations to be accurately checked as part of an overall integrated calibration strategy for the arm, mast and PanCam.

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