

BEAGLE2 SIMULATION, KINEMATICS CALIBRATION, AND ENVIRONMENT DEM GENERATION

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ABSTRACT

Beagle2 [1] as part of the ESA Mars Express mission [2] will be launched in June 2003. The primary science goal of Beagle2 is to search for the presence of life on the planet with the aid of a sophisticated package of scientific instruments [3]. These include mass, Mössbauer and X-ray spectrometers, a microscope, stereo camera system (SCS), and environment sensors. All but the mass spectrometer are mounted on a structure called the PAW, which also carries a mole device (PLUTO) to obtain sub-surface, and/or under rock samples, and a corer/grinder to remove weather rind from rock surfaces. Deployment of the PAW is achieved using a robot ARM that has been designed and built by Astrium Ltd [4]. The operation of the ARM with its PAW ‘end-effector’ is therefore of paramount importance during the mission, and considerable effort has been expended to validate its performance, and to provide ARM software tools that can be used during mission operations. The work has involved the creation of a virtual Beagle2 software simulation, kinematics calibration, and subsequent PAW SCS calibration and Beagle2 environment DEM generation. This paper provides details our work in these areas, together with the results that we have obtained when using our calibrated Beagle2 simulation to generate ARM joint angle data which have been used to command the real Beagle2 ARM.

BACKGROUND

The Space Robotics Group at Aberystwyth has received Beagle2 ARM, PAW, lander base, and lander lid CAD data from Astrium and the Space Research Centre (SRC), Leicester. This has been imported into a robot simulation software package, ENVISION(TR) [5], to create a virtual Beagle2. The strategy is to use this virtual Beagle2 during the mission so that engineers and scientists can validate, and plan the operation of Beagle2 on Mars, before commanding the real Beagle2 ARM to move. The stereo camera system (SCS) mounted on the PAW will capture images of the Martian terrain, and software developed by Joanneum Research, Austria, is able to convert this data into a 3D terrain digital elevation model (DEM). When in this format, Martian terrain information can be imported into the Beagle2 virtual model, which will enable the scientists and engineers to ‘fly’ around the Beagle2 virtual environment, and visualise rocks and the Martian surface, in their search for the best science targets. Once these have been selected, the virtual Beagle2 can be used to ensure that the targets can be reached by the ARM and PAW, and that no part of the ARM and PAW will collide with neighbouring rocks, or any other part of the Beagle2 lander. For the virtual Beagle2 model to be used in this way, the software model must be calibrated with the real Beagle2, so that the virtual and real ARM kinematics are identical. The Aberystwyth group has completed the generation of the virtual Beagle2 model, together with the necessary

	Theta: R[z]	d: T[z]	a: T[x]	Alpha: R[x]	Beta: R[y]
Joint 1	126.947	0.000 mm	134.260 mm	0.000 deg	0.000 deg
Joint 2	-173.053 deg	-28.579 mm	1.182e-005 mm	90.000 deg	0.000 deg
Joint 3	0.011 deg	-22.800 mm	378.300 mm	0.000 deg	0.000 deg
Joint 4	179.988 deg	0.999 mm	330.900 mm	0.000 deg	0.000 deg
Joint 5	0.000 deg	85.371 mm	9.487e-006 mm	90.000 deg	0.000 deg

Figure 1: Beagle2 ARM Denavit-Hartenberg parameters.

DM and FM ARM kinematics calibration. The stereo cameras are calibrated relative to the ARM and PAW, thus enabling camera images to be obtained and DEM data generated, for importing into the virtual Beagle2 environment. Having created a calibrated virtual Beagle2 model, together with the DM ARM terrain DEM generation work, we have conducted a number of tests to investigate the performance of our calibrated model when used to command a real ARM based upon Envision(TR) generated joint angle data. This paper presents our work in creating a virtual Beagle2, calibrating this model with the real Beagle2 DM and FM ARMs, using the calibrated virtual Beagle2 model and calibrated PAW/SCS to generate a terrain DEM, and finally, the tests that have been performed to validate the operation of the virtual Beagle2 model plus imported DEM, when being used to generate joint angle data to command a real Beagle2 ARM.

VIRTUAL BEAGLE2 SIMULATION

Envision(TR) is a mature robot simulation software product that has a long industrial track record and exposure to demanding robotic applications. The software is able to import Catia CAD part data, which is an essential capability, and allows Astrium and Leicester designed Beagle2 parts to be imported into the simulation environment without any modification to that data. Once within the Envision(TR) software environment, the parts can be ‘assembled’ into a virtual Beagle2, complete with lander base, lid, robot ARM and instrument PAW. Hence given that the Beagle2 parts have been machined as per their Catia design, the virtual Beagle2 is geometrically identical to the real Beagle2 (within manufacturing tolerances). Once assembled, a kinematics model for the robot ARM and other moving Beagle2 parts can be created. The conventional robotics Denavit-Hartenberg (D-H) method [6] has been used to define the parameters required for deriving the forward and inverse kinematics model for the Beagle2 ARM. D-H parameters for the uncalibrated Envision(TR) ARM model are shown in figure 1.

Texture maps and VRML data can be imported into the virtual Beagle2 simulation, thus allowing Martian panoramic camera images, Wide Angle Mirror (WAM) images, and Martian DEM terrain data to be visualised within the same virtual Beagle2 environment, see figure 2. Using this Beagle2 model we can mount a virtual camera on the virtual PAW SCS (or elsewhere) thus obtaining a virtual pre-view of the subject(s) under investigation using the real SCS. The resolved motion capability of the ARM (inverse kinematics), allows automatic ARM configuration(s) generation, automatic ARM/PAW working envelope generation, joint-by-joint motion for mission planning and operations, and ARM joint data readout ready for conversion to ARM potentiometer values prior to their transmission to Beagle2 on Mars. ARM/PAW/Lander/DEM collision detection can be performed and Envision(TR)’s Graphical Simulation Language allows mission scripting and rehearsal. User definable lighting (i.e. Sun position), and resultant shadowing on the ground is possible together with a user definable Envision(TR) GUI for Lander Operations Control Centre (LOCC), and Lander Operations Planning Centre (LOPC) activities.

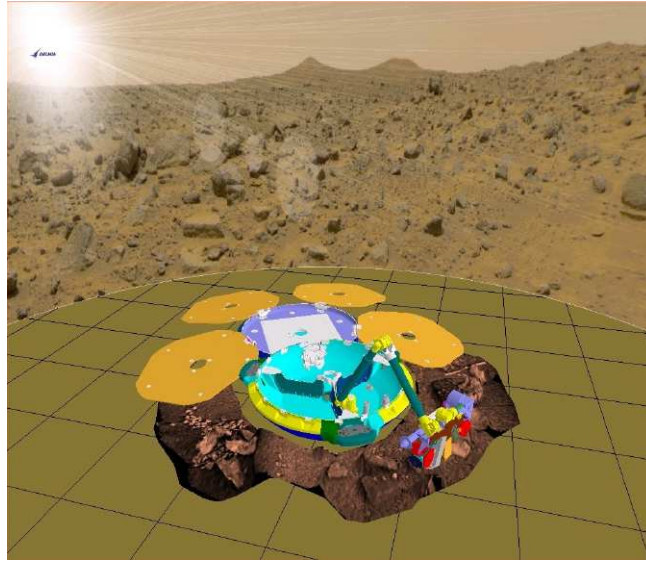


Figure 2: Beagle2 simulated in Envision(TR) with imported panoramic camera image backdrop (image courtesy of NASA/JPL), and terrain DEM.

BEAGLE2 KINEMATICS CALIBRATION

Once the virtual Beagle2 simulation has been created, this model must be calibrated with the real Beagle2 so that it can be used for mission planning purposes. The Beagle2 simulation can generate the robot ARM joint values for a desired configuration and position in Beagle2 Cartesian space. These joint values will then be uploaded to the real Beagle2 on Mars. Hence the kinematics of the virtual and real Beagle2 ARM must be identical. Our calibration measurement system included a Vicon 512 infra-red camera motion capture system [7], and a 1 *arcsecond* theodolite. During calibration, the real ARM was moved to a number of positions and orientations within its operating envelope, and these were measured using our Vicon measurement system. The key regions for calibration are the GAP (Gas Analysis Package) Inlet Port, the lander base calibration target, and the DEM terrain region (see section: CALIBRATED BEAGLE2 DM AND FM ARM TESTS). Prior to calibrating the virtual Beagle2 model, ARM joint potentiometer/angle validation tests, and ARM/PAW repeatability tests were undertaken using the Vicon measurement system.

For real/virtual ARM calibration, real joint angle and Vicon data were imported into the Envision(TR) environment. A Levenberg-Marquardt [8, 9] nonlinear least squares fit was performed between the Vicon data and the virtual ARM when commanded to move to the same positions and orientations as the real ARM. This resulted in the modification of the virtual ARM joint-offsets so that its kinematics matched those of the real ARM. Figure 3 shows the calibration setup. Two of our seven Vicon cameras are shown in the background. The 1/3rd mass PAW is a rapid prototyped volumetrically identical PAW with a mass equal to that of the real PAW on Mars. Hence ARM deflections comparable with those that will be experienced on Mars were produced. Figure 4 shows the FM ARM calibration setup. The reflective spherical markers used by the Vicon system can be seen, and these were mounted coaxial with each PAW instrument. The group of three reflective markers that can be seen in figure 4 were used to reference the ARM (attached to its base mounting plate) to the Vicon ‘L-Frame’. This L-Frame defined our calibration origin, and can be seen to the right of the ARM in figure 3. The base plate markers to L-Frame measurements were obtained using the theodolite. For the FM calibration work, the ARM links, base plate, and clean room floor were covered with low-reflecting materials to prevent stray reflections from ceiling lights etc. affecting the Vicon cameras. For the DM work we simply turned the lights out - which was not an option in a busy clean room! The 1/3rd mass PAW was bagged to prevent any residual dust (produced by the rapid prototyping process) from entering the clean room.

Due to the excellent correspondence between the as-designed/as-manufactured/as-imported into Envision(TR) ARM part geometric parameters (a tessellation SAG value of $0.02mm$ was used for the Envision(TR) part import process), the original D-H parameters of the Beagle2 ARM were retained during the calibration process.



Figure 3: Calibration setup with the Beagle2 DM ARM, 1/3rd mass PAW, and mock terrain.



Figure 4: Calibration setup with the Beagle2 FM ARM and 1/3rd mass PAW in Astrium Ltd. clean room.

Rather the original ARM joint offsets were modified. Prior to calibration, the joint offset for each of the 5 joints was set to 0.00 *degrees*. The result of the joint offset calibration can be seen in figure 5. Calibration of Joint 1 required the largest joint offset angle correction. The joints are numbered: Joint 1 - ARM Body, Joint 2 - ARM Shoulder, Joint 3- ARM Elbow, Joint 4 - ARM Wrist Upper, and Joint 5 - ARM Wrist Lower. The next stage in the calibration process was to calibrate the PAW SCS, and undertake a number of theodolite measurements of the PAW so that it can be referenced to the calibrated Envision(TR) virtual ARM/PAW model during mission operations.

PAW SCS CALIBRATION AND BEAGLE2 ENVIRONMENT DEM GENERATION

Prior to environment DEM generation, the PAW stereo camera system (SCS) must be calibrated. The first stage includes an internal camera calibration to determine lens distortion, interior orientation and relative orientation between the cameras. Camera image data of a SCS camera calibration target was obtained for this operation. Figure 3, to the left of the ARM, shows the top of this calibration rig. This first stage was performed initially using the 1/3rd mass PAW which was fitted with COTS cameras. This allowed the SCS internal camera calibration process to be rehearsed and refined using the DM setup, prior to performing the process on the final FM PAW SCS under clean room conditions.

The second camera calibration stage involved the determination of a ‘Zero PAW State’ whereby the relationship between SCS and the ARM was noted. This state is a nominal position outside of the lander base that has the SCS pointing down towards the terrain region, see figure 6. The Zero PAW State will be a position that the ARM will be commanded to move to during Martian terrain SCS image collection. A Zero PAW State was determined both for the DM and FM ARMs. A Helmert Transform is used to generate a Cartesian vector and rotation matrix between any image data obtained from the SCS, when on Mars, and Zero PAW State, thus allowing the position and orientation correspondence between a SCS image and the Envision(TR) virtual ARM to be calculated. Figure 7 shows a diagram of this process. 6 fixed points on the PAW were chosen (e.g. a sharp corner of an instrument), and with the ARM positioned in the Zero PAW State, the Cartesian position of each PAW point was calculated from measurement data obtained using the theodolite. The position of each point was calculated relative to a local coordinate frame origin, (figure 7 shows only 3 PAW points for simplicity, and shows CF1 as this coordinate frame). During FM PAW SCS calibration, the PAW was not attached to any Beagle2 ARM. The process took place at a different geographic site (SRC, Leicester). The FM PAW and FM

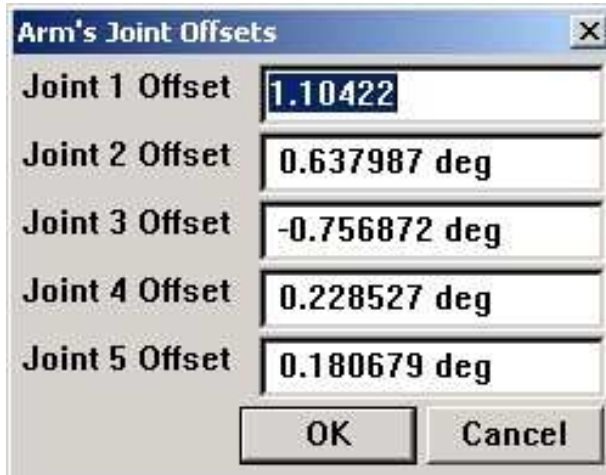


Figure 5: Beagle2 ARM joint offsets after calibration.



Figure 6: Beagle2 FM ARM and 1/3rd mass PAW in Zero PAW State position.

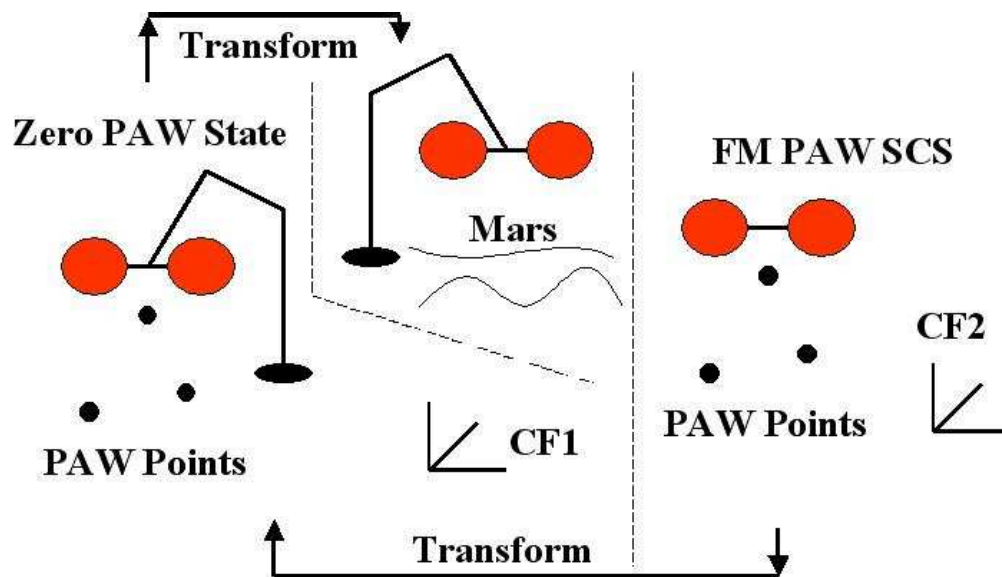


Figure 7: Helmert Transforms are used to map SCS image data captured in one coordinate frame system (CF2) to another, ARM relative coordinate frame system (CF1). The larger (red) circles joined by a line depict the SCS. Fixed points on the PAW (only 3 are shown here) are depicted by the smaller (black) circles.

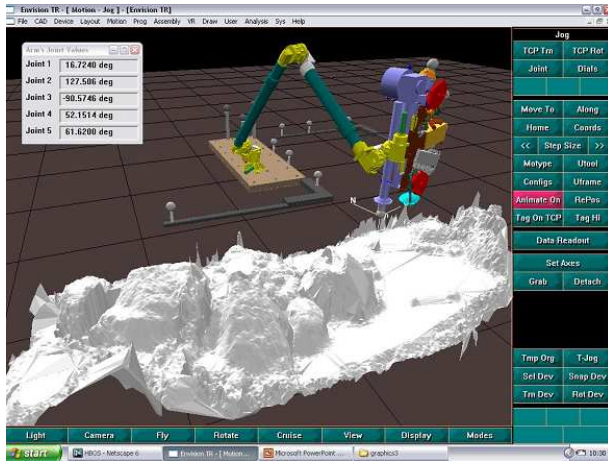


Figure 8: Envision(TR) screen dump showing calibrated Beagle2 ARM and PAW, plus imported terrain DEM (ortho RGB texture map not shown).

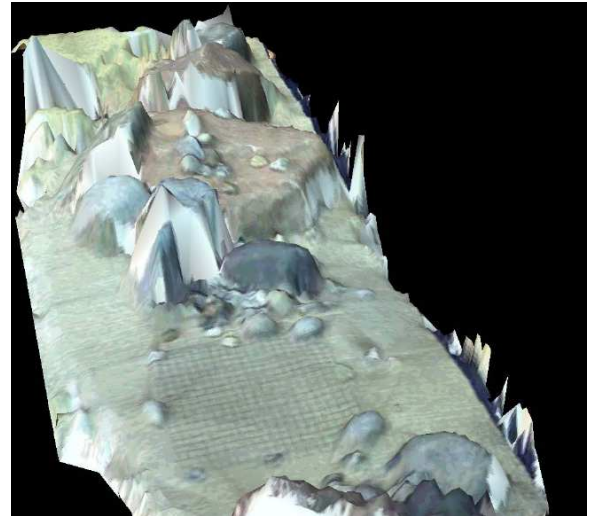


Figure 9: Imported terrain DEM plus ortho RGB texture map. The mock terrain rocks and pebbles can be seen clearly, together with a 1cm grid in the foreground.

ARM only come together once they are all in the FM base. Hence, during FM PAW SCS calibration, the same 6 fixed PAW points were measured, but this time relative to a different local coordinate origin, shown as CF2 in figure 7. Given this information, any image gathered by the SCS (where ever it may be) can be transformed with the aid of a Helmert transform from one coordinate frame to another, i.e. from CF2 to CF1. As CF1 relates to a know ARM configuration (Zero PAW State), then the gathered images can likewise be related to this state. When on Mars, as the ARM is moved, then so will the 6 PAW points move, and the Envision(TR) calibrated ARM/PAW model can be interrogated to determine the new virtual PAW point positions. Using a Helmert transform once more, will enable a gathered SCS image to be transformed to its correct ‘on Mars’ position, relative to the ARM Zero PAW State.

To generate a terrain DEM, the terrain under investigation is imaged by moving the ARM with attached PAW SCS over the terrain surface at a height determined by the cameras’ focusing range. The combination of a statistical based hierarchical feature vector matching method, and Helmert Transforms on the stereo image data, allows a DEM mosaic to be generated. The resultant DEM can be rendered with the captured camera ortho RGB images and exported as a VRML file. Once in this format, the DEM and ortho RGB texture map can be imported into the virtual Beagle2 Envision(TR) environment. Figure 8 shows an Envision(TR) screen dump. The calibrated ARM and PAW are shown together with an imported terrain DEM. This was generated from camera data gathered by moving the ARM and 1/3rd mass PAW during the DM calibration work. The mock terrain shown in figure 3 was used. Figure 9 shows the same DEM, but this time it has been rendered with the ortho RGB texture obtained from the camera images. Note the white (no data) regions in figure 9, which is due to terrain occlusion. This could be remedied by obtaining further images at different SCS positions and orientations.

CALIBRATED BEAGLE2 DM AND FM ARM TESTS

There are three key regions within the Beagle2 work envelope that the ARM must be able to move to, and position the PAW and selected instrument with both an accuracy and repeatability better than $\pm 5mm$. These regions are (1) the *GAP (Gas Analysis Package) inlet port* (Martian soil samples collected by PLUTO are deposited within the GAP inlet port for analysis by the mass spectrometer), (2) the *calibration target* (used by the PAW instruments for measurement calibration); and (3) the *DEM terrain region* where sites of scientific interest will be examined by the PAW instruments. During the calibration process, considerably more Vicon measurements were taken in these key regions, than elsewhere within the ARM’s work envelope. Figure 10 shows results from the ARM repeatability studies when operating in the DEM terrain region.

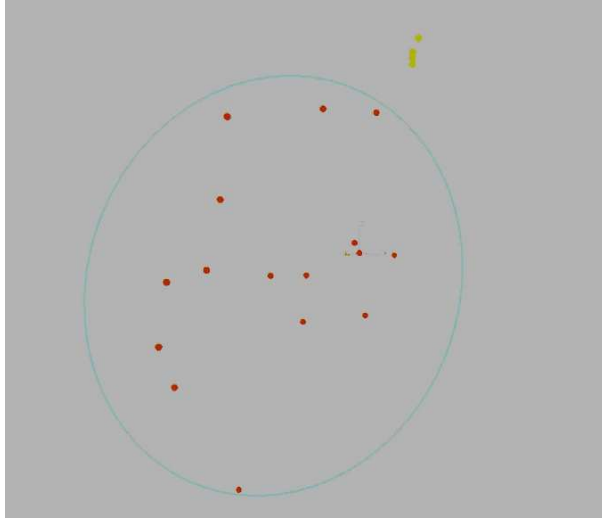


Figure 10: Real ARM/PAW repeatability results when commanded to a location within the DEM terrain region.



Figure 11: End-to-end DM ARM and 1/3rd mass PAW tests using virtual ARM/PAW model, and mock terrain.

The ARM was moved to a number of different start positions, and from each of these start positions, the ARM was commanded to move to the same goal position in the DEM terrain region. Vicon measurements were taken of the ARM after it had reached the goal position. Figure 10 shows the Vicon data, and each measured goal position is represented as a small sphere of diameter $0.1mm$. A bounding sphere was created such that all the smaller spheres resided within its volume. This larger sphere represents a repeatability volume, and is shown in figure 10 as a circle of diameter $\approx 8mm$. It was observed that due to the ARM's proportional control, there was always a small overshoot on each joint (typically $\approx 0.1degree$), also joints 4 and 5 suffer from backlash due to the bevel gears in their drive train (joints 1 - 3 employ a direct drive from their harmonic gearboxes). Due to this overshoot and backlash, when the ARM joint potentiometers were interrogated, it was observed that the ARM was not exactly at the joint values that had been used to command the ARM to move to the goal position. To overcome this, the ARM was re-commanded to move once more to the same goal position. Whilst this manoeuvre could not overcome the overshoot (which is very predictable), it did serve to remove the backlash on joints 4 and 5. The resultant effect was a considerable improvement in the ARM's repeatability. Figure 10 shows a small group of spheres to the top right of the circle. These spheres were constructed from Vicon measurements taken at this re-commanded goal position. The locus diameter for this group of spheres was measured to be $\approx 0.6mm$, well within the desired repeatability of $\pm 5mm$. The repeatability study was performed for the GAP inlet port, and calibration target regions, and the same re-commanded goal position repeatability improvement was observed. Repeatability without re-commanding the ARM to move to the GAP inlet port and calibration target goal positions was measured to be $\pm 1mm$ in both cases. After we had conducted the ARM repeatability studies, virtual/real ARM accuracy investigations were conducted once a terrain DEM had been obtained. As part of our DM calibration work, SCS images of a mock Martian terrain were obtained by commanding the real ARM to move over the terrain. This data was processed to generate a terrain DEM, which was then imported into the virtual Beagle2 environment. The virtual Beagle2 PAW instruments were moved in turn to a location on the DEM surface, virtual ARM joint values were obtained for each PAW configuration, and this data was input into the real ARM command interface. The motion of the real ARM was then observed and measured to compare virtual and real instrument end position and orientation, see figure 11. Additionally, tests were performed using the calibrated Envision(TR) model to obtain joint data for commanding the real ARM to position instruments on the calibration target, and to insert the mole into the GAP inlet port. Figure 12 shows the Envision(TR) model with the mole Vicon marker positioned directly above, and level with the GAP inlet port. Envision(TR) was interrogated to obtain the virtual ARM joint values for this position. These values were input to the real ARM command interface, and the real ARM was observed to move to this position with an accuracy better than $\pm 1mm$ in axes x , y , and z . Encouraged by this finding, we removed the Vicon marker from the mole on the 1/3rd mass PAW, updated the virtual model accordingly, and obtained new Envision(TR)

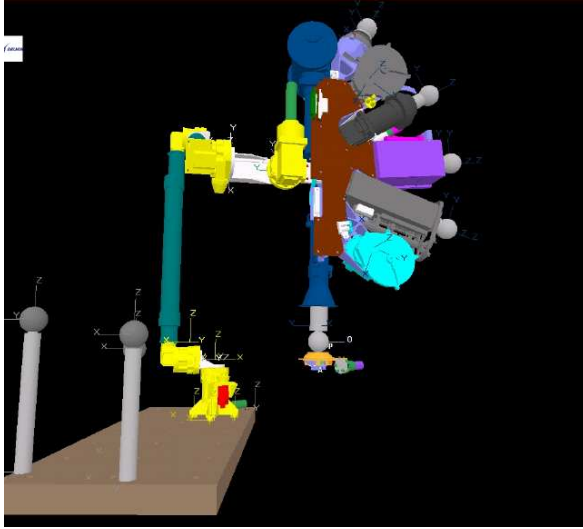


Figure 12: Calibrated Envision(TR) model with ARM and PAW positioned with the mole Vicon marker directly above and level with the the GAP inlet port.



Figure 13: FM ARM and 1/3rd mass PAW shown after being commanded to position the mole in the GAP inlet port using Envision(TR) generated ARM joint data.

generated joint values for a position with the mole inserted in the GAP inlet port. These joint values were then input into the FM ARM command interface, and the motion of the real ARM was observed. Figure 13 shows the outcome of this motion. The mole was successfully inserted into the GAP inlet port using ARM joint data obtained from our calibrated Envision(TR) Beagle2 model. To conduct this test, a duplicate GAP inlet port was fixed to the ARM base plate in exactly the same position that it occupies in the lander base. A duplicate calibration target plate was also fixed to the ARM base plate, and this can be seen to the bottom of figure 13. A similar successful test was performed using the calibrated Envision(TR) to obtain joint values for commanding the FM ARM to position an instrument (e.g. X-ray spectrometer) against the calibration target plate.

CONCLUSION

We have successfully created a virtual Beagle2 model using the Envision(TR) software simulation package. This model has been calibrated with both the DM and FM ARMs, and we have rehearsed the process of generating a terrain DEM using the PAW SCS, real ARM and Envision(TR) software. We are now in a position to generate joint values for commanding the FM ARM on Mars. Currently we are working on the interface and detailed operations of our virtual Beagle2 simulator both at the Beagle2 Lander Operations Control Centre (LOCC), situated at the UK National Space Centre, and the Lander Operations Planning Centre (LOPC), situated at The Open University, UK. We will report on this work in future literature.

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