VALIDATION OF SPACE VEHICLE DOCKING WITH THE INTERNATIONAL BERTHING & DOCKING MECHANISM AND A KUKA ROBOT

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ABSTRACT

The validation campaign results are presented for the European International Berthing and Docking Mechanism (IBDM) intended for space vehicle docking. The validation was performed using the first prototype of this mechanism together with a KUKA robot manipulator carrying as payload the passive IBDM counterpart. The docking of the ATV with the ISS was very closely emulated as was demonstrated by the high correlation of representative contact forces measured during the tests and those contact forces predicted by high fidelity simulations. Furthermore, the IBDM control was also successfully validated in its capability to align itself with the passive counterpart while experiencing large relative kinematic initial configuration errors near its capture envelope and representative approach velocities.

1. IBDM REQUIREMENTS & DESIGN

The International Berthing and Docking Mechanism (IBDM) is a c ontact force sensing, magnetically latched for capture, low impact docking system, capable of docking and berthing large and small vehicles. Mechanically, it is an actively controlled 6-DOF parallel manipulator powered by six linear actuators. Functionally, the IBDM consists of two systems, the soft docking system and the hard docking system. The soft docking system captures and actively damps the two spacecraft. The hard docking system makes the structural pressurized connection between the two spacecraft and is responsible for the service connections and the nominal and emergency separation functions.

The IBDM was initiated as a j oint development programme by ESA and NASA JSC, with the purpose of enabling the berthing/docking and attachment of the CRV to the ISS. Since the cancellation of the CRV program, ESA has progressed on the IBDM alone developing a prototype mechanism and accompanying avionics with SENER Ingeniería y Sistemas S.A. and Verhaert Space. The validation of this first prototype is consequently presented here.

The IBDM is conceived to have the capability to perform docking for a wide range of vehicles as well as being more robust with respect to the relative docking kinematic alignment errors than if it were purely passive. The active IBDM system drives the actuators to move the guiding ring in order to align the active IBDM and passive IBDM systems. The 21 ton ATV has been selected as the baseline docking vehicle together with the 400t ISS. For this purpose, the linear electro-mechanical actuators designed by SENER supporting the top ring must deliver linear forces up to 650N in order to achieve the necessary contact forces required to dampen and halt the opposing docking vehicle, while achieving linear velocities of 170mm/s to match the maximum potential relative approach velocity. Equally important is the long available stroke length of 290mm for each actuator granting the mechanism the available workspace to manoeuvre sufficiently given the maximum kinematic configuration errors between the docking vehicles.

The permitted kinematic configuration errors which define the capture envelope of the mechanism are listed in Table 1 below. Note that the Z-axis is aligned with the principal direction of docking. The variables Vx, Vy, Vz are the time derivatives of the X, Y, Z position of the passive IBDM docking platform.

Table 1. Docking misalignment and velocity tolerances.

	minimum	maximum	units
Roll	-5	5	deg
Pitch	-5	5	deg
Yaw	-5	5	deg
X	-5	5	cm
Y	-5	5	cm
Roll Rate	-0.5	0.5	deg/s
Pitch Rate	-0.15	0.15	deg/s
Yaw Rate	-0.15	0.15	deg/s
Vx	-1	1	cm/s
Vy	-1	1	cm/s
Vz	-10	-5	cm/s

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The maximum kinematic configuration errors which define the capture envelope are those maximum relative configuration values of the passive vehicle when the Docking Interface Plane is crossed. The Docking Interface Plane, as later drawn in Figure 4 which describes the Validation Plan, is the plane parallel to the IBDM top-ring at a 0.2m distance in the direction away from the active IBDM (Z>0), which is slightly farther than the tips of the IBDM petal structure.

The contact forces between docking vehicles are measured in the active IBDM by six load cells aligned at 45 degrees between a top and mid-ring as displayed in Figures 1 and 2. These are specified to measure in excess of 1000N linear force from which a 6-DOF contact force vector may be determined. No other relative distance information is available to the active control mechanism from sensors or communication links. It must rely completely on the experienced contact forces and changes to its own configuration, i.e. the linear actuator lengths.

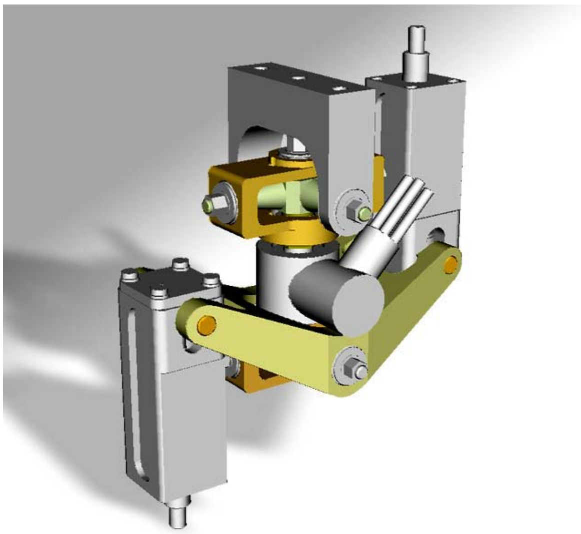

Figure 1. Load cell (with overload protection) assembly.

The standard docking procedure may be summarised as a succession of the following phases [1]:

Friction Estimation: A set of vertical movements are performed by the active IBDM platform in order to on-line estimate the friction levels in each actuator. A set of parameters are identified according to a friction model individually for each actuator.

Extraction: Operations are performed by the GNC of the approaching vehicle (Chaser) to satisfy the kinematic docking alignment error conditions. Meanwhile, the active IBDM fully extends itself and waits at a predetermined position until contact occurs.

Capture: This phase begins with the first contact between vehicles. The guide petals align mechanically as the actuators align actively the opposing mechanisms. The actuators move the upper platform in order to establish a stable contact between the two platforms. Once the opposing rings are aligned and make contact, the electromagnets, whose capture range is very short, are energised.

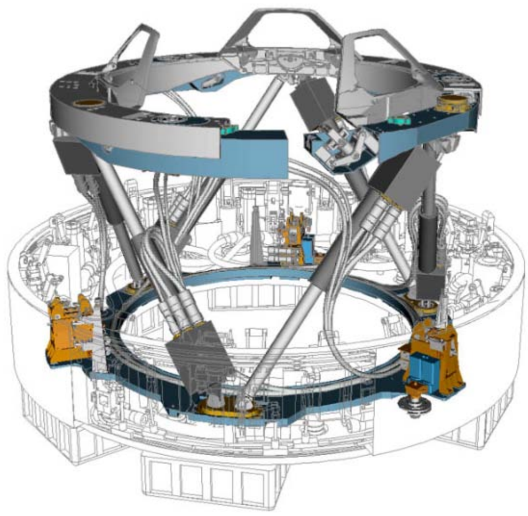

Figure 2. Drawing of IBDM mechanical design.

Damping: The actuators act to reduce the relative velocity to zero between the two vehicles in a controlled manner within the constraints of their workspace.

Retraction: The IBDM is positioned so that its orientation and linear position are aligned vertically above the hard-docking latches. The platform is then slowly vertically retracted to the position where hard-docking structural connection is performed.

Structural connection: A series of latches are engaged which establish a structural connection between the IBDM and the vehicle (hard-docking).

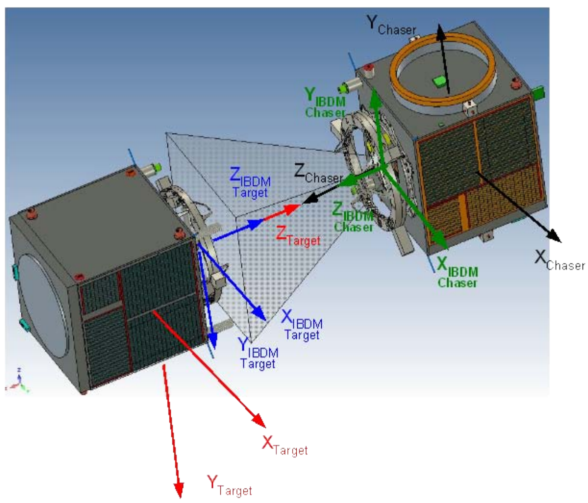

Figure 3. Lightweight Vehicle Docking.

2. IBDM VALIDATION PLANNING

The first two phases of the docking procedure have a straightforward validation plan in as far as they only depend upon the IBDM and do not require special test facilities. The validation consists in reproducing the required movements of setpoint control and trajectory tracking associated with the on-line friction estimation and extraction operations. Both consist of performing primarily vertical motions of the 6-DOF platform and determining the final convergence error to the desired point or trajectory.

The remaining docking phases are much more difficult to validate as they require the docking vehicle or at least that part which may emulate the contact dynamics representative of the docking vehicle. In the case of the IBDM, the primary docking vehicle for which the mechanism has been designed for is the 21 ton ATV. This naturally presents serious difficulties for the validation in reproducing the contact loads that such a vehicle would produce.

The scheme that was elaborated which permitted the validation of at least the Capture phase among the remaining docking phases was the use of a KUKA robot to carry the passive IBDM androgynous component. The KUKA may be then programmed to perform a straight-line constant velocity trajectory. The complexity of the validation manoeuvre may be reduced by not requiring a force feedback to the KUKA or the implementation of a 6-DOF force sensor in the tool tip. Such a feedback or sensor plus additional complex relative dynamic calculations and a high force bandwidth force feedback control implementation would normally be necessary to reproduce exactly the relative dynamics in space. Nevertheless, the very massive 21 ton ATV docking vehicle configuration has as an advantage that its own dynamics is very little affected during the initial seconds of the capture phase. The typical forces employed by the active IBDM to align itself with the docking vehicle are small enough as to not influence sufficiently the docking vehicle's motion. It is during the successive damping phase that the entire actuator power is necessary to bring the docking vehicle to a halt, though with this proposed simple validation test procedure this validation manoeuvre is not possible.

The docking vehicle validation test plan is divided into three test categories.

1. **Robot test platform characterisation - Trajectory tracking performance:** The KUKA manipulator endpoint should follow several constant velocity trajectories in several downward directions emulating a capture scenario, all within the capture envelope defined by the values given in Table 1. The robot's ability to track the required reference trajectories effectively is determined.

   A total of five reference trajectories are selected with increasing difficulty with respect to increased kinematic configuration errors and approach velocity. All trajectories involve a non-frontal collision with a varying degree of petal-petal contact before the very rigid opposing rings contact each other. This is to avoid excessively large collision forces and not to overstress mechanical components during initial tests. A slower approach speed of 2cm/s outside the standard capture envelope is also selected for the first two trajectories in order to first permit the validation of the contact force levels predicted in simulation.

2. **Robot test platform characterisation - Trajectory tracking performance under force bias and disturbance:** Following the same trajectories as in test category 1, the KUKA's ability to track the required reference trajectories effectively under the presence of a constant resistive force plus disturbances shall be determined. These disturbance inputs serve to characterise the influence on the KUKA trajectory tracking performance due to the initial contact forces that shall be experienced upon contact with the IBDM.

   The passive IBDM is attached to the manipulator endpoint. Several masses in the range of 5 to 20 kg are attached to the endpoint with a chain such that a constant downward force acts upon it. Additionally, the mass is perturbed midway through the trajectory in order to simulate a collision. The mass range is selected based upon the expected contact forces from simulation results when the passive IBDM collides with the active IBDM.

3. **Docking emulation:** Following the same trajectories as in test categories 1 & 2, the passive IBDM upheld by the manipulator endpoint should track these same reference trajectories which, however, now lead to a collision with the IBDM. The IBDM docking control performance in its capture phase shall be evaluated according it its ability to align itself with the passive counterpart.

It is assumed that the IBDM will occupy a space of approximately 0.7m height from the ground. In order to emulate a capture scenario, the manipulator endpoint should follow reference trajectories such that it reaches the maximum downward velocity and maintains it in the range from 0.9m down to 0.5m above the ground.

The passive IBDM is attached to the manipulator endpoint. The active IBDM is situated below the robot in such a manner that the passive IBDM makes contact with the active IBDM within its capture envelope. Initially, a *soft control* shall be used in the first trajectory before using a representative control law (the *soft control* will minimize contact forces between passive and active parts of the IBDM) [2].

The developed Avionics equipment monitoring and controlling the active IBDM may also be configured to introduce various safety measures to prevent excessive unexpected contact forces from damaging the mechanism using the actuator length inputs and load cell force measurements.

The specific safety measures that were implemented are:

- The active IBDM is turned off when the *Stop Motion Plane* of Figure 4 is reached resulting in an immediate downward motion of the active IBDM away from the passive counterpart mounted on the KUKA.
- Once a force threshold is surpassed in the load cell measurements, the active IBDM is turned off.
- The KUKA reference trajectories are programmed such that they penetrate a maximum of 10cm into the active IBDM workspace below the IBDM extraction setpoint. After the reference trajectory endpoints are reached, the KUKA arm immediately comes to a halt.
- Common grounding of both items (robot and IBDM) shall be checked in advance and reviewed before the test execution.

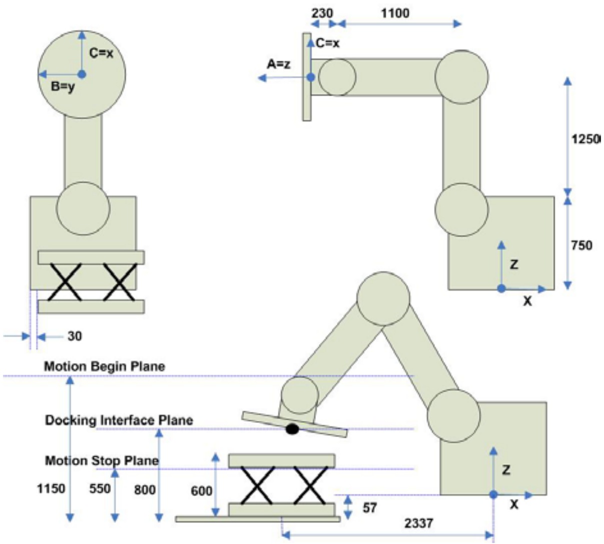

Figure 4. KUKA and IBDM coordinate frames and motion planes schematic.

In Figure 4, the Motion Begin Plane, Docking Interface Plane and Motion Stop Plane are illustrated. These planes indicate the trajectory begin, capture envelope definition and trajectory end respectively. Though the mechanical guide petals are not drawn in Figure 4 (visible in Figure 2), the Docking Interface Plane lies slightly above the upper extremity of the guide petals at 0.2m above the IBDM top-ring.

3. IBDM SOFTWARE PRE-VALIDATION

This mechanism has been developed with a mechanical construction phase in parallel with the programming of a high fidelity simulation environment. This includes a very complete IBDM and docking vehicles' dynamic model which served to corroborate and influence the mechanical design, depending upon the required performance and expected characteristics of space docking predicted by the simulator [3].

The IBDM simulation tool is intended to simulate the relevant electro-mechanical aspects of the IBDM soft-docking process. The simulation model of the IBDM is responsible for simulating the following elements:

- dynamic behaviour of the active mechanism, including the actuator dynamics
- relevant aspects of actuator motor dynamics
- global vehicle dynamics upon which the active mechanism is attached
- global vehicle dynamics upon which the passive mechanism is attached
- collision and contact dynamics between the passive and active IBDM platforms
- electromagnet - striker plate force relationship
- sensory behaviour of the load cells, actuator length sensors, electromagnet micro-switches

Additionally, the IBDM dynamics simulation interacts with a digital control law responsible for the active soft docking control by providing it with sensory input information and receiving EMA motor torque request commands [2].

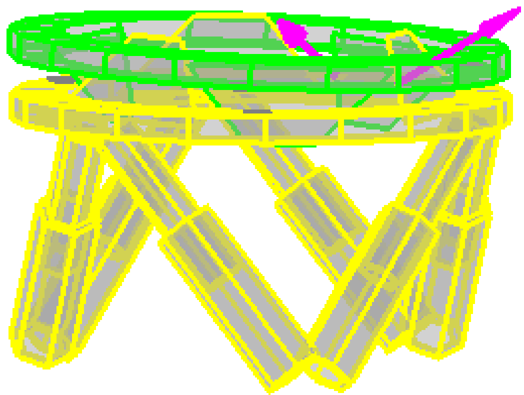

Figure 4. Passive (green) and active (yellow) IBDM simulation animation model with interacting contact forces (purple).

The contact dynamics determine the resulting contact forces arising during contact of the passive IBDM with the active IBDM platform. Contacts may occur between either the petals or the platform top-ring. In each case, the penetration vector(s) for the i^{th} contact is determined at the point of maximum penetration and perpendicular to the contact surface. For each contact a linear force vector is calculated from a virtual spring-damper model. Modelling the contact forces with the opposite IBDM platform during docking as a virtual spring-damper depending upon the penetration depth and relative velocity at the point of penetration decouples the dynamics between the two vehicles so that the contact forces may be calculated apart from the forward dynamics calculations and then introduced in each dynamic system as an external force.

The test cases described in the previous section were first simulated in the simulation environment. This step was important in order to obtain a prediction for the experienced contact forces, IBDM motion and capture performance.

The simulated test case results are displayed below for test case 5 in Figures 5-6. The simulated load cell forces serve as a preliminary measure to ensure that the mechanical limits shall not be exceeded. They also serve to define appropriately the implemented safety measures in the avionics equipment controlling the mechanism which abort the validation contact test when the load cell forces exceed the designated limits.

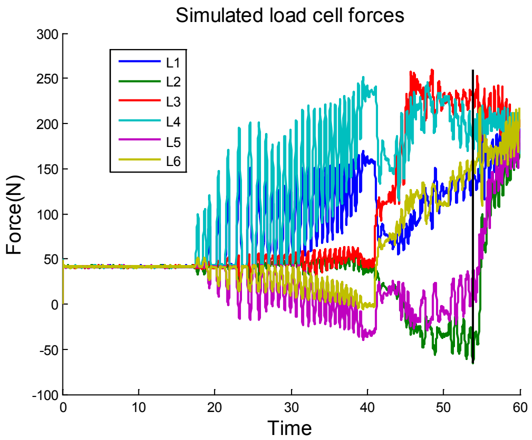

Figure 5. Simulated load cell forces during contact for Test Case 5.

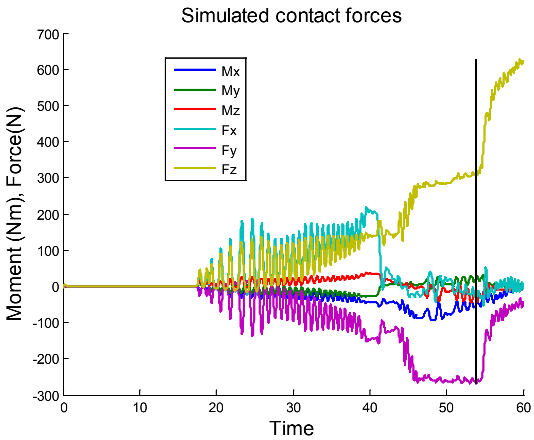

Figure 6. Simulated contact force vector during contact for Test Case 5.

The black vertical lines in Figures 5 & 6 indicate when the Capture phase has completed with a p erfect alignment which may be measured by the triggering of contact switches located at each of the three electromagnets on the active top-ring surface. The contact force wrench in top-ring coordinates is obtained via a co nfiguration-independent Jacobian transformation. In Figure 6, one may see that the primary experienced contact force is the vertical linear force shortly before and after capture.

4. IBDM HARDWARE VALIDATION

In a collaborative effort with GMV, a KUKA KR 150-2 robot within the Madrid INTA (Instituto Nacional de Técnica Aerospacial) installations has been programmed to reproduce the test reference trajectories representative of a 21 ton ATV vehicle as commented in Section 2. Attached to its tool interface is a passive rigid IBDM docking interface. In front of the KUKA robot, the IBDM is mounted horizontally on the ground. See Figure 12.

An avionics electronics platform was developed for controlling and sensing the movement of the IBDM Stewart platform mechanical configuration and experienced contact forces during the docking process. This avionics was also validated with a simulation-in-the-loop setup using dSpace real-time hardware running the simulation environment.

As reported in Section 2 in test category 1, the reference test trajectories implemented on the KUKA robot confirmed the robot's capability to perform the constant velocity trajectories with only negligible error. The subsequent tests performed in test category 2 also permitted a c haracterization of the compliance level expected by the KUKA tool tip when subject to the level of collision forces to be experienced during a docking experiment.

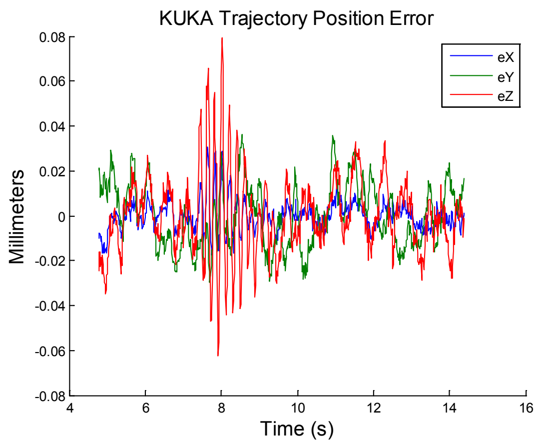

Figure 7. Sample test case of KUKA trajectory tracking while experiencing a force disturbance.

Figure 7 di splays the position tracking error when a force perturbation is introduced during the tracking of the fourth reference trajectory with an additional 5kg constant force disturbance bias being introduced as well. The tracking error of 0.06mm attributable to the force perturbation indicates an inherent compliance in the KUKA approximately equivalent to that present in the active IBDM of about 600N/mm. This value validates the predicted contact forces from simulation without the need for adjustments neither in the predictions nor in the active IBDM control.

The trajectories were then repeated with the IBDM in the trajectory's path. Several safety measures were introduced to prevent damage to the mechanism such as defining the KUKA trajectory endpoint at a maximum of 10cm below the nominal active top-ring level. In addition, in the event of the sensed contact forces were to exceed a set limit within the load cells, the IBDM aborts the capture process. This value was first set to 390N, and then scaled up to 547N, 612N and 684N upon necessity for the more demanding trajectories and upon validating the alignment of the measured forces with the predicted forces.

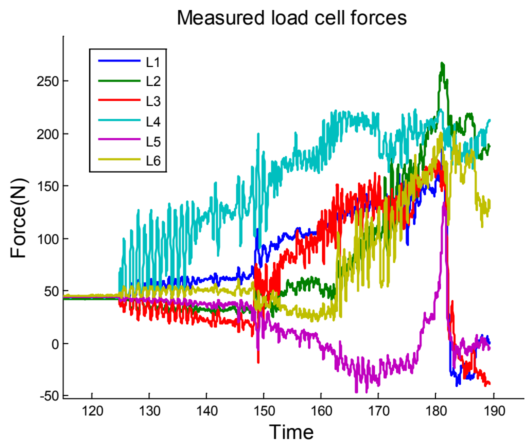

Figure 8. Measured load cell forces from test trajectory 5.

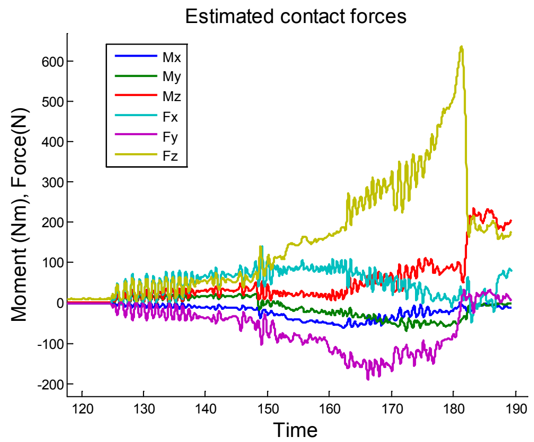

Figure 9. Contact force wrench from test trajectory 5.

Figures 8 and 9 illustrate the measured contact forces from a sample test trajectory which may be compared with Figures 5 and 6. A high-level of correlation between them is apparent demonstrating the utility of the simulation environment to predict the contact forces. The variables demonstrate a strong correlation between each other. One must take into consideration that the irregular contact geometry makes it very difficult to synchronize perfectly both movements. Most importantly, one may see that the overall tendencies and magnitudes of the forces are very similar.

The IBDM accomplished finally many difficult capture manoeuvres within its 'capture' envelope. The test results from the most difficult test achieving capture (full alignment with contact switches depressed between opposing rings) are shown in Figures 10 and 11. The trajectory is characterized by near extreme kinematic configuration errors and an approach velocity of 7.5cm/s of the passive IBDM.

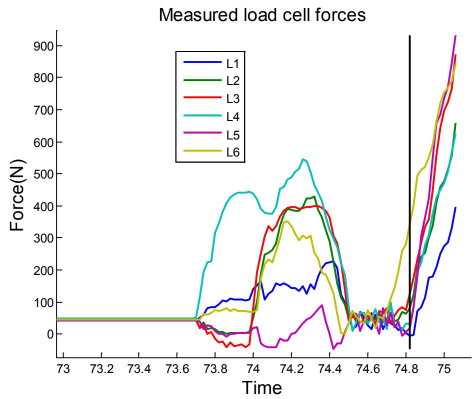

Figure 10. Measured load cell forces from test trajectory 5.

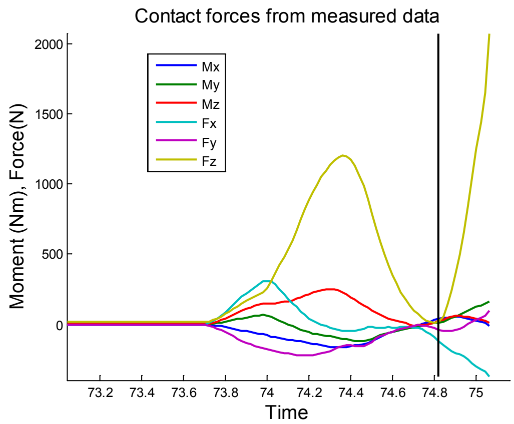

Figure 11. Measured load cell forces from test trajectory 5.

These tests have served to gain much insight into the connection between the dynamic behaviour and the active control strategy necessary for successful space docking.

First, they have demonstrated the utility of a high fidelity simulation to predict in advance the expected mechanical conditions of real hardware experiments. In fact, such experiments were only planned due to the availability of such predictions which indicated that they would provide useful data. Second, with a rather simple and straightforward test facility configuration, in comparison with other space vehicle test sites, very representative and valuable was gathered for the development of this mechanism.

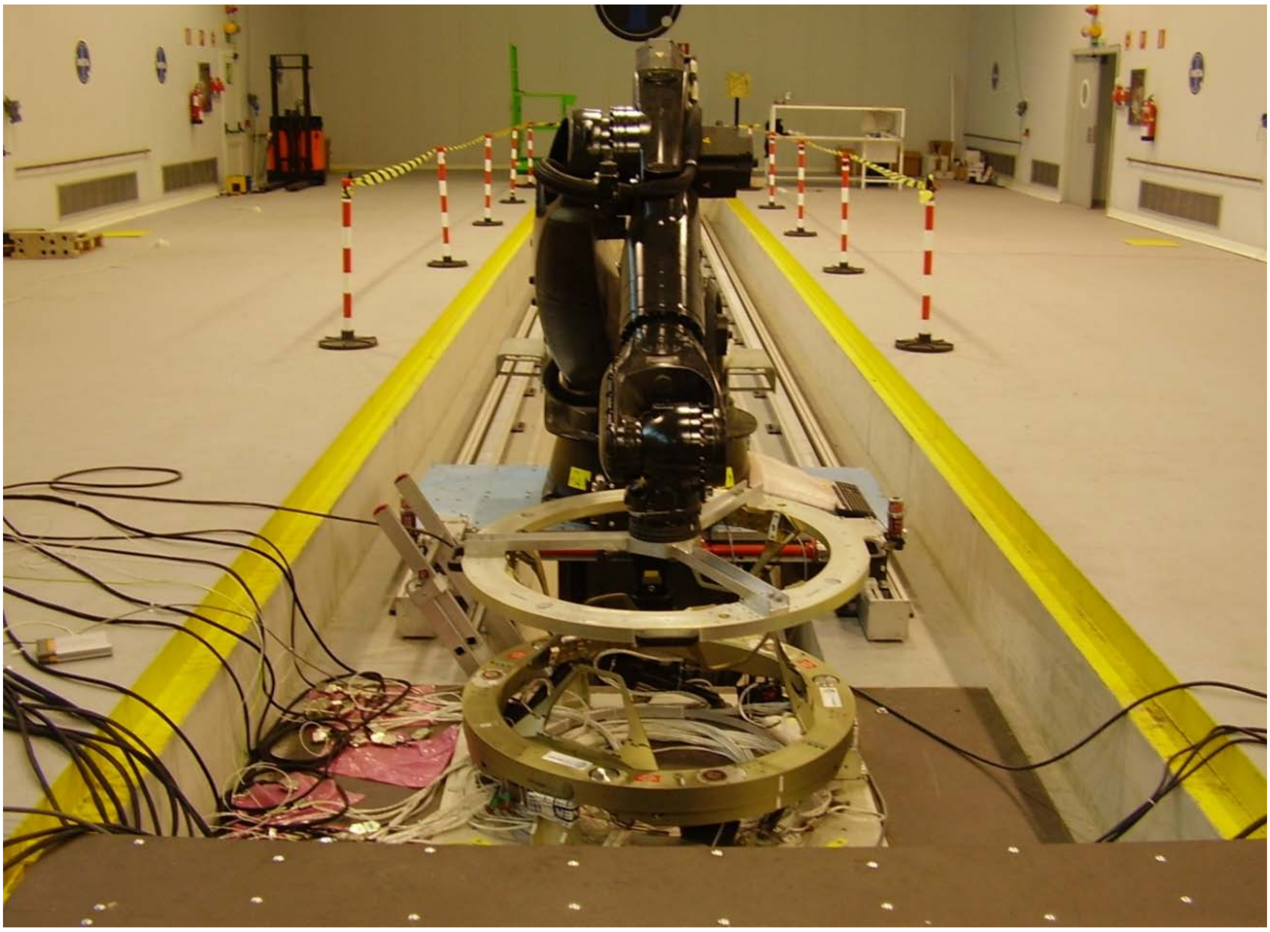

Figure 12. Validation test facilities in INTA, Madrid, Spain

The ability to achieve capture under extreme kinematic configuration errors and moderate approach velocities exceeded the validation expectations for the initial tests of the first developed prototype. Nevertheless, the tests have also served to identify points which may be improved upon in successive designs.

5. IBDM MECHANICAL REDESIGN

In spite of the relatively good observed performance observed during the contact tests reported here, the high correlation of measured contact forces with simulated results confirm the difficulties that this mechanism has in achieving capture with a wider range of docking vehicle masses and approach velocities. Recall that this mechanism is intended to serve as a universal docking platform for the spectrum of different space missions that are being planned. The relative contact dynamics, however, may have quite different characteristics with an order magnitude difference in vehicle mass. It has been recognized that precisely with light docking vehicles, the capture process becomes extremely difficult due to high system rigidity and actuator friction.

The high system rigidity make the system little robust to sudden impact forces and very difficult to control when regulating contact forces in the capture phase. These impact forces may grow to be very large as the controller cannot react sufficiently fast to counteract them. Consequently, the IBDM system is pushed away slightly until another impact occurs. This process is repeated over and over again many times until either an alignment is successful and capture occurs or a rebound takes place. As each impact translates into a sudden loss of relative velocity between the two vehicles, there is very little margin for controlling with respect to the impact forces in order to align the docking platforms before the entire relative kinetic energy has been consumed. This deficiency is predicted to be most acute when docking lighter spacecraft with less inherent kinetic energy.

The second major difficulty is the high level of actuator friction. Since the maximum deliverable actuator force of 650N is scaled such that docking may be performed with the 20 ton ATV spacecraft, large transmission ratios are necessary in the actuator produce these forces. Consequently, large static and dynamic friction levels are present which the actuator must overcome. A precise estimation of the friction forces is necessary in order to compensate them correctly since the actuator must be able to deliver actuator output forces sufficiently accurate in almost the complete force range up until its maximum value. The IBDM must perform force control for docking as a 20ton spacecraft as well as positioning an unloaded 30kg table.

A new actuator design is, consequently, in process which shall include a compliant load sensing device that should greatly aid in improving these two major existing deficiencies in the IBDM design.

First, the compliant load sensing device attaches to the extreme end of the actuator where it connects to the upper platform. The softer spring forming part of the compliant load sensing device reduces the overall system stiffness by more than an order of magnitude. This has a large benefit during docking as the contact forces do not grow nearly as rapidly, and the controller has time to react to the estimated contact forces and promote alignment in a stable manner. On the other hand, the actuator control becomes more sophisticated in order to counteract oscillations in the passive elements and achieve the desired output actuator force.

Second, the load measurements obtained from the compliant load sensing device additionally serve to provide a direct feedback of the forces acting in-line with the actuator; thereby significantly aiding in the estimation of the actuator friction forces. Additionally, it is not expected that the orientation of the load cells in the actuators should significantly reduce the estimation quality of the contact forces. Nevertheless, a higher quality friction estimation is considered to be more important than a very exact measurement of the contact forces. Such an implementation is considered to be more robust as it may be better equipped to compensate changing dynamic and friction model parameters under different ambient conditions.

The overall docking goals of the IBDM have been established to accomplish docking of spacecraft with masses between 2 and 21 tons under the same previous kinematic error conditions of the capture envelope. This mechanical redesign concept serves to enlarge the dynamic force range for which the active IBDM mechanism may regulate the contact forces from this wide set of docking conditions.

6. CONCLUSION

The work presented here describes the validation plan, its execution and results for a space docking mechanism. This validation work successfully culminates a lengthy design phase involving several partners and complex design work in mechanics, simulation, control, software, and electronics, all coming together in the end. It is notable that the validation procedure involved a standard industrial robot which was programmed to perform manoeuvres performing representative space docking motion profiles. Such a procedure presented a cost-effective manner to gather valuable and useful data in order to progress in the design of successive and improved prototypes of the European space docking mechanism.

Capture scenarios were reproduced for an emulated 21 ton ATV docking with the ISS. This involved the alignment of the active IBDM with its passive counterpart. Additionally, the test reference manoeuvres corresponded to extreme configurations in the required capture envelope. The final results confirmed the next planned steps in the subsequent mechanical redesign of the mechanism.

7. ACKNOWLEDGEMENTS

An important part of the success of this program is due to the contribution of QinetiQ Space (formerly Verhaert Space) in the design, construction and validation in a significant part of the IBDM mechanism. We also recognize the important contribution made by INTA in permitting the use of their installations and their support during the validation program.

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