

DEXTROUS LIGHTWEIGHT ARM FOR EXPLORATION (DELIAN)

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ABSTRACT

The DELIAN project aims at studying and subsequently developing the technology building blocks that would aid the development of a class of robotic arms for the future Martian rovers and landers.

Key issues of this development are the very limited resource allocation in terms of mass, power and volume as well as high performance requirements. A conceptual arm design is conducted for different mission application scenarios. Families of joints are identified which will be used as building blocks for the arm. A selected joint is further designed and developed at engineering model level. Preliminary test results are included. The arm control system is described, suggesting specific solutions for controlling a very lightweight arm as DELIAN.

1. INTRODUCTION

The robotic exploration of Mars has been identified as one of the main objectives for Europe in the field of planetary exploration. For this purpose, ESA's Mars Robotic Exploration Preparation (MREP) Programme proposed a Technology Development Plan (TDP) identifying key enabling technologies to be developed within Europe to support on-going and future planetary missions.

The DELIAN project belongs to the robotics and rover technologies theme of the MREP TDP and aims at developing a generic lightweight robotic arm, as a technology building block to enable "accessibility" to the Martian surface either for sample acquisition, sample retrieval or instrument deployment as part of a rover or a lander platform.

The work to be performed within the context of the activity is split in three technical phases, which comprise an incremental development scheme:

- Phase 1: DELIAN definition (mission analysis, system requirements and architectural design);
- Phase 2: development and testing of a joint prototype, control system simulation and breadboarding;
- Phase 3: DELIAN arm development and functional testing.

Phase 1 is focused on analysing a variety of mission scenarios and subsequently defining the requirements and architecture of the elements that need to be developed, resulting in different robotic arms in size, force/speed capability and positioning accuracy. For each arm, number of degrees of freedom (DoF), joint/limb mass and length are allocated based on the overall arm mass, length and kinematics requirements. Accordingly, several joint concepts are studied and evaluated for suitability to the demanding DELIAN requirements. A scalability analysis is performed and four families of joints are identified which will serve as building blocks for the arm.

Finally, within phase 1, the end-to-end control architecture is specified, from the low-level servo control functions to the arm-level coordinated control.

Within phase 2 a detailed design of a single joint is produced, built to Engineering Model (EM) standards. Components are selected/customised to achieve a compact and lightweight joint. The design is optimised based on the result of supporting analyses, including structural and thermoelastic analyses, to confirm that the joint is suitable for testing within the required operating temperature range. The joint test campaign comprises functional and environmental testing in Martian conditions with two goals. The first is to characterise and validate the novel joint design. The second is to compile a set of test data that would serve as a reference for future projects/missions to assess the performance of similar designs in early stages of the development.

In parallel to these activities, the DELIAN control system is analysed in the control and software domain, to support the design through simulation models and breadboarding.

In the frame of the incremental approach of the activity, phase 3 aims at detailed design, manufacturing and testing of a Development Model (DM) of a complete robotic arm for planetary exploration.

The paper is mainly focused on the results of phase 1 and 2. The joint EM test campaign is currently on-going and some preliminary results are included.

2. MISSION ANALYSIS AND REQUIREMENTS

DELIAN system requirements are derived from the analysis of four mission scenarios, mainly related to Mars missions but also including a low gravity body mission [6]. For each of the application scenarios an activity analysis is performed, identifying the operational tasks and consequently deriving the main requirements and constraints, such as workspace, positioning accuracy, operational force and payload capability.

Robot arms resulting from this process have different characteristics, ranging from small (less than 1 m) to longer slender arms (more than 3 m). They must provide operational force at the end effector from 10 to 30 N, handle payloads from 1 to 6 kg with minimum resource consumption (arm mass from 3 to 9 kg, excluding payload harness and end effector, electrical power from 8 to 40 W). To achieve this goal, they are allowed to move at low velocity (required joint velocity is 0.7 deg/s). Sometimes they require however quite good positioning accuracy (1.5 to 5 mm for some specific tasks).

3. DELIAN ARM CONCEPTS

3.1. Architectural design approach

Starting from system requirements, the arm architecture is derived and components (joints, limbs) are preliminary sized. Following this initial allocation, a set of analyses and trade-off activities is performed to support the design, mainly:

- At arm level, kinematics and load analyses;
- At joint level, architectural trade-off and scalability analysis.

The kinematics analysis is conducted as follows.

Different kinematics configurations are derived considering:

- Roll, pitch or yaw joint types combined in a different sequence;
- Arrangements of offsets to allow different stowage configurations (in-line, single offset - at wrist, multi offset - at elbow and wrist).

In total, five candidate 6 DoF kinematics structures have been analysed and compared based on the outcome of the following set of analyses:

- Dexterity, as the capability to reach workspace points with different approach directions;
- Capability to execute trajectories: both with horizontal and vertical tool orientation;
- Kinematics and static performance at the end effector (Cartesian velocity, force, accuracy and repeatability);
- Tolerance to kinematics failures (locked joints).

The result is a selection of the preferred kinematics configurations for the four application scenarios.

The DELIAN joint design is conducted in parallel to the arm design, with the purpose of supporting the definition of the arm budgets and at the same time, through a scalability analysis, deriving a suitable joint architecture that can be scaled up or down into a discrete (small) number of different joints that can serve all the different applications.

In total, four families of joints have been identified and sized sufficient to cover all DELIAN application scenarios.

Starting from the results of kinematics analysis and joint scalability analysis, the final geometrical configuration of the arm is derived and all kinematics parameters are finalised after the implementation of a 3D CAD model. The CAD model incorporates the joints selected from the families that match the required torque, interconnected with properly shaped limbs (in terms of dimensions and thickness); the harness routing and encumbrance is also analysed and included in the CAD model.

In parallel with the CAD design, a load analysis is conducted both in stowed configuration and operational configuration.

The preliminary design solutions for robot arms covering the applicable scenarios are described in the paragraphs here below.

3.2. Scenario A: acquisition of a cached sample

This scenario applies to a mission where a rover is responsible for collecting and bringing back samples left by another vehicle to the lander. A possible reference mission is the Sample Fetching Rover [1] [2] (part of Mars Sample Return). The robotic arm is a small 5 DoF arm with a length of 0.87 m and a mass of about 3.2 kg. The maximum horizontal workspace (distance from arm base to cache pick up location on the soil) is about 0.5 m.

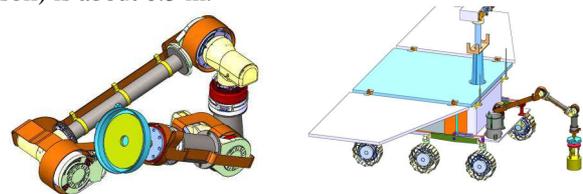


Figure 1. Scenario A, sample fetching rover

3.3. Scenario B: scientific instrument deployment

This type of scenario is applicable in the context of a lander mission. Reference missions could be Mars Geodesy and Environment Network (MarsGEN) [3] and Mars Network Science Mission (MNSM) [4]. The arm is required to pick up and deploy a number of different instruments. However, the sizing factor is the placement of the heaviest instrument, a 6 kg seismometer, in the Martian gravity at 1.7 m distance from the lander. The

result is a 4 DoF arm with a length of 2 m and a mass of about 5.1 kg.

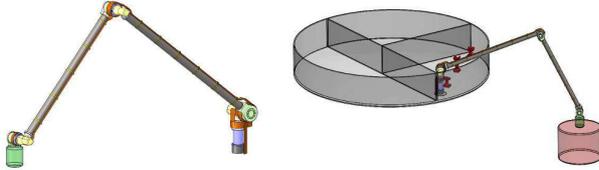


Figure 2. Scenario B, scientific instrument deployment

3.4. Scenario C: sample collection and deposition

This has been further divided in two sub-scenarios:

- C1. “Excavator” like arm for sampling mission (e.g. Phoenix [5]); the robotic arm is equipped with scoop/blades that enable sample collection from the planetary surface, or immediate subsurface, and subsequent deposition of the sample to an analytical instrument (or a caching mechanism). The result is a 4 DoF arm with a length of 2.2 m and a mass of about 5.6 kg;
- C2. Multipurpose arm for sample return (e.g. [6]). Besides sampling/coring, the arm can perform other operations (e.g. opening of the re-entry capsule, exchange of end effector, latching/unlatching). The result is a 5 DoF arm with a length of 3.6 m and a mass of about 8.3 kg.



Figure 3. Scenario C1, sample collection and deposition

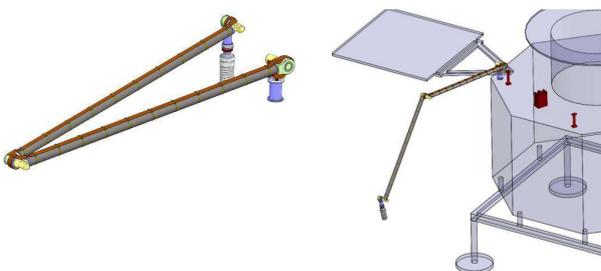


Figure 4. Scenario C2, sample collection and deposition

3.5. Scenario D: scientific instrument placement

This scenario refers to instruments being placed on a workbench at the tip of the arm and being positioned against targets for scientific measurements. This type of scenario is applicable in the context of both a lander and a rover mission. Some reference missions are the early ExoMars [7] and Spirit and Opportunity Mars

Exploration Rovers (MER) [8]. The arm is a 5 DoF robot with a length of about 1.4 m, a mass of about 4 kg, capable of handling a 2.5 kg payload, with several instruments. The required positioning accuracy is 1.5 mm.

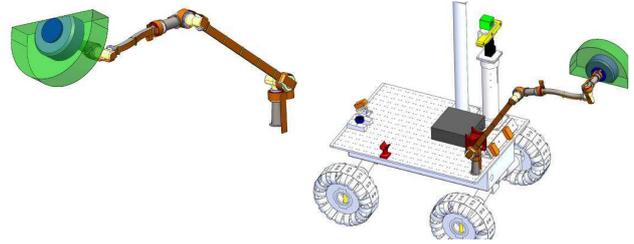


Figure 5. Scenario D, scientific instrument placement

3.6. Arm subsystems

Besides the joints, the main arm subsystems have been studied as part of the architectural design, including limbs and harness.

Concerning the limbs, even if from a pure structural point of view the use of carbon fibre for the long limb cases could turn out to present some advantages (anyway attenuated by the small diameter of the limbs) issues as CTE matching to the bearing steels and housings used in the actuators and the possibility of an ‘easy’ fitting of strain gauge sensors (if needed), favour the utilisation of a metallic solutions, especially in Titanium.

Concerning the arm harness, in principle two approaches are possible, based on flat cables or on separate bundles. The flat cable approach should allow for efficient mass and volume exploitation. Due attention is however needed to the traces layout especially as far as EMC/shielding robustness and protection against dust/powder. The separate bundle approach could be a bit more robust and shieldable, but not optimal when a large number of wires is needed. Routing of optical fibres has also been considered, either with a single (un-split) fibre from the instrument to the platform or by splitting the fibre optic into separate parts and interface the parts across the joints.

Although not strictly belonging to the arm module, also complementary subsystems have been addressed such as the hold down and release mechanism, the arm parking system and the jettison system.

3.7. DELIAN arm development model

A DM of DELIAN arm will be developed and tested in phase 3 of the project. The DM will be obtained from mission scenario D but will be based on a 6 DoF kinematic structure, to enhance its versatility when employed as a general purpose arm in the laboratory environment. A configuration with a limb reshaping solution is proposed (Fig. 6) that allows the implementation of a spherical wrist and a very high dexterity at the same time. Partial use of innovative technologies such as additive manufacturing can be

considered for the limbs and the interconnecting elements, to minimise the number of mechanical parts, saving mass and improving mechanical accuracy.

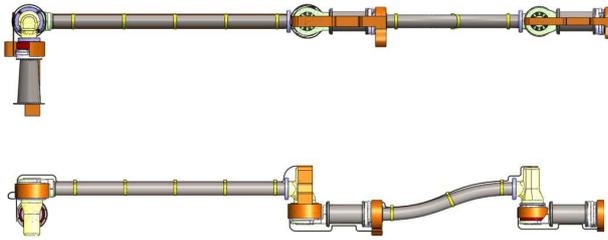


Figure 6. DELIAN arm DM (two views)

At the end of phase 3, the arm will be calibrated and the functional performance of the system as a whole will be tested under earth gravity within the predefined test scenarios. The estimation of flexibility and its parameterisation into the controller model are an important aspect to be duly considered in order to achieve the very demanding positioning accuracy requirements.

4. JOINTS

4.1. Design Approach

The aim of the DELIAN activity is to study “families of joints” that would serve as building blocks for different robotic arms. In total, four different mission scenarios have been analysed in order to derive specific arm level requirements. For an arm working in a gravitational environment, the force/torque required at joint level depend on the location of the joint and its utilisation. The approach at joint level has therefore been to group the various set of requirements into families of joints enabling to build all identified robotic arms.

The focus has been to select motor and sensors capable of covering the full range of joints and to adapt mainly the reduction stage and structural elements to the various required torques and forces. The main challenge was to select scalable mechanical and electrical elements through the full family while minimising parts, overdesign situation and the related mass penalties.

4.2. Scalability Analysis

The maximal required output torque has a direct impact on the joint design and in particular on the mass and volume. Therefore it is important for the scalability rules to find a relationship between motor mass and mechanical output torque specification. A detailed component and joint level survey has been performed in order to define engineering rules and suitability of existing hardware in the context of DELIAN.

The comparison of the harmonic drive with the planetary gear mass to torque equation is shown in Fig. 7. It demonstrates that harmonic drive technology is

lighter when the gear output torque exceeds 0.5 Nm.

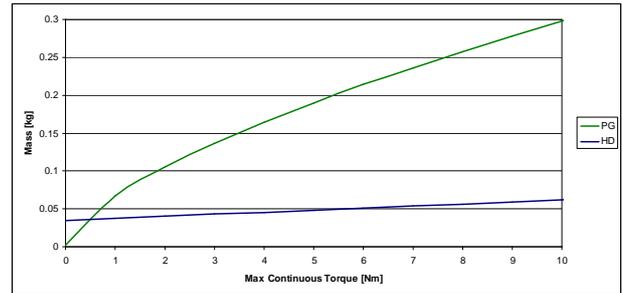


Figure 7. Harmonic Drive/Planetary Gear Comparison

However, this analysis does not consider the efficiency that, in particular at low temperature, is in favour of planetary gears. A reason not to use a harmonic drive for the first stage is that the efficiency of harmonic drives decreases significantly with an increase of rotational speed. Therefore best mass to torque ratio is achieved with a relatively light motor and high reduction ratio composed of a planetary gear and a harmonic drive with maximum available reduction ratio.

In Fig. 8 the red line is the mass to torque relation derived from the NASA IDD actuators and the blue rectangles show the estimated DELIAN actuators modular designed with commercial available components. The torque capability is calculated with no margin but under worst case conditions, i.e. estimated efficiencies of the gears in worst case environmental conditions.

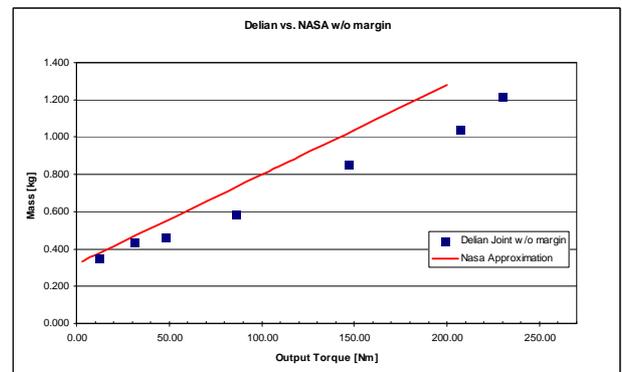


Figure 8. DELIAN study vs. NASA actuator

4.3. Design Overview

The joint of family #3 has been manufactured with interface allowing integration into a robotic arm. The architecture is a straight configuration consisting of a maxon motor ag brushed DC motor (equipped with a 8 count/rev motor position sensor), a planetary gear and a harmonic drive gear stage of type CPL-2A 17. An accurate Anisotropic Magneto Resistive (AMR) angular position sensor with two indexes for motion limits has been integrated directly at the output shaft. The number of counts per revolution, including interpolation, is 376'000. This provides a resolution of 0.001° and

accuracy of $\pm 0.003^\circ$.

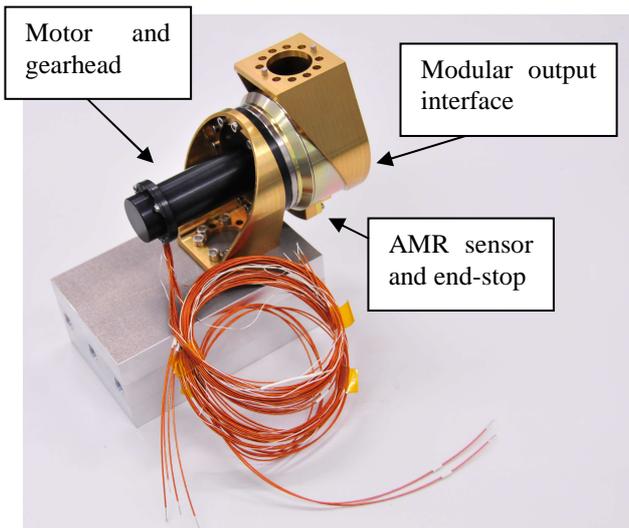


Figure 9. EM Joint overview

The dimension fits in a cylinder of $\text{Ø}66 \times 105 \text{mm}$ without the external sensor. The small protrusion required for the three sensor head is of $\text{Ø}74 \text{mm}$. The overall mass without the harness and interfaces is only 0.68 kg for the EM and is expected to be 0.59kg for the FM. The continuous output torque capability is 54Nm and at least 38Nm including ECSS margin in worst-case operational conditions. For integration into an arm, the load to be taken in operational configuration are up to 60N in all directions, 80Nm in bending and peak torque of 79Nm is to be produced. This peak torque to mass ratio is in line with the estimation reported in Fig. 8. For continuous torque capability the torque to mass ratio is optimistic and some margin needs to be applied.

The joint has been designed and manufactured to operate on Mars or the Moon environment with a temperature range from -55°C to $+60^\circ\text{C}$. An extended test campaign will assess the capability to operate at a lower temperature of -70°C and survive -128°C to $+100^\circ\text{C}$.

4.4. Test Results

The testing is still on-going. Under ambient condition, the 54Nm could be produced when applying 3V and 0.2A at motor level. Because the motor can operate under 24V, significant motorisation margin can be demonstrated. The motorisation margin will be confirmed during Thermal Vacuum (TV) testing. The rotation speed is greater than 0.7deg/s and stable signal from output sensor can be recorded and used for position control.

The measured joint stiffness is linear and in the order of 10^7 N/m and 10^4 Nm/rad . The FEM analyses confirm suitability of this joint to survive typical random and quasi-static loads occurring during launch, transfer and landing phase.

Heater and TCs have been implemented. They allow to determine the required heating power from survival to operational temperature as well as keeping the COTS sensor head warm during TV testing.

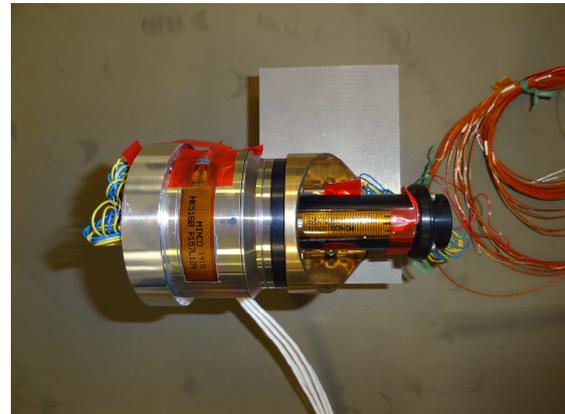


Figure 10. EM Joint with thermal hardware

The holding torque capability is above 20Nm. Still, this is not sufficient to maintain the arm position in power-off mode for most joint configurations. Therefore a passive brake will be added to the FM.

A first lesson learned is that modifying the input interface of the harmonic drive to accommodate the planetary gear limits the output torque capability. Therefore the expected peak torque at 1-g conditions could not be generated and, for joints requiring this capability, the original harmonic drive shall be used. This modification will increase the length of the joint, though.

The joint produced confirms suitability of the design for use within a robotic arm and confirms the outstanding capability in term of mass to torque ratio and position accuracy. A second joint of lower capability using same motor and output sensor is in the design phase in order to validate the scalability approach and provide the required number of models in order to build a full arm.

5. CONTROL SYSTEM

The DELIAN control system is composed of the On-board Control System and the Ground Control Station (GCS), both with the relevant hardware and software. These components are functionally and physically embedded within the ground and the space segments of the overall planetary exploration system and mission, of which DELIAN will be part.

5.1. On board control system

The DELIAN On-board Control System is depicted in Fig. 11 and includes:

- The On Board Computer (OBC) and software;
- The low level motion control electronics.

This is a general scheme which aims at covering the

wide spectrum of DELIAN scenarios.

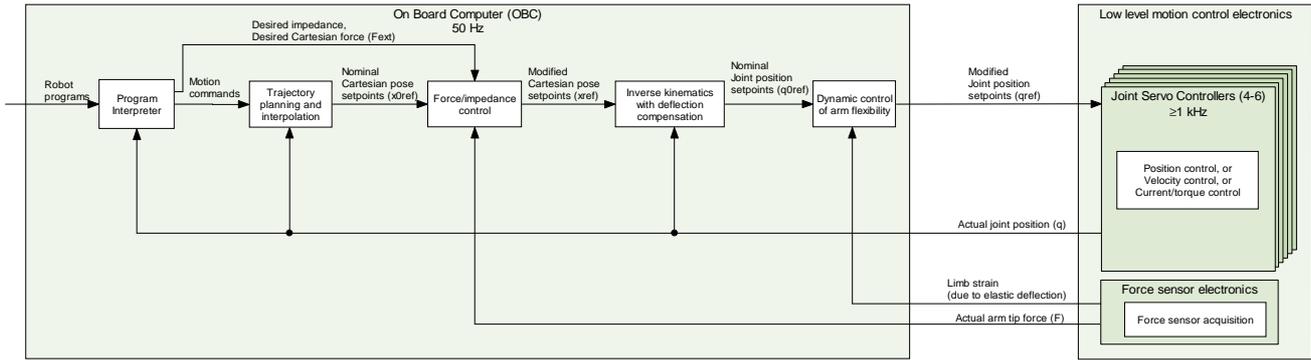


Figure 11. DELIAN on board control system

A central controller, residing in the OBC, is in charge of Cartesian arm control, while a number of joint servo controllers (one for each degree of freedom) and a force sensor electronics are in charge of interfacing the arm for low-level control and sensor acquisition. The presence of a force sensor is application dependent.

Robot programs, either prepared by the ground segment or by an on-board autonomous agent (deliberative planner), are loaded into and executed by the on board program interpreter, which generates motion instructions handled by a trajectory planner. The planned trajectories are interpolated at e.g. 50 Hz, generating Cartesian pose setpoints which are transformed into joint position setpoints through the inverse kinematics module. The inverse kinematics includes a module for online deflection compensation. Other deflection compensation methods are possible, as described in section 5.1.2 below.

Joint position setpoints are transmitted to the joint controllers, which perform joint servo control, ensuring that the actual joint positions follow the desired setpoints. In turn, the joint servo controllers transmit back actual joint position as telemetry data.

Contact motion operations (e.g. instrument placement with preload) can be performed using the force sensor signal, acquired by the force sensor electronics and transmitted to the OBC. The OBC can adjust the desired Cartesian position based on the desired external force compensation, through an implicit force based or impedance based compensator.

Finally, a module for controlling arm flexibility improves the dynamic control performance in case of very flexible arms. This block can use strain gauge signals from the limbs and adapts the nominal joint setpoints to achieve a trajectory that is basically free of oscillations caused by the arm main natural frequencies. Some interesting elements of the control system are discussed in more details here below.

5.1.1. Joint servo control

The joint servo control ensures that the joints follow the desired position setpoints received from the OBC. Both static and dynamic performances are relevant. In fact,

DELIAN has challenging requirements for both static positioning and path accuracy.

Concerning static positioning, an accurate sensor is available on the output shaft, therefore the preferred solution is to close the joint position control loop on this output sensor.

Concerning dynamic accuracy, the key issues affecting the performance of joint control are torque disturbances, such as ripple and friction, which are speed dependent, and gearbox torsional flexibility, which depends on the load and the inertia (and therefore on arm posture and payload characteristics). Typically torque disturbance can affect the performance at low velocity, while joint flexibility can affect the performance in high inertia configurations.

In general, torque disturbance can be compensated with a high-bandwidth motor control loop. However, this adversely affects the performance, as it creates lightly damped poles on the load side. Trade-offs between torque disturbance compensation and damping of the load behaviour have to be sought.

The proposed solution is to employ a dual-loop cascade control scheme, with an inner motor velocity loop closed on the motor sensor and an outer joint position loop closed on the output sensor. The two loops must be balanced to achieve a good trade-off between large bandwidth (LB) of the inner loop and large damping (LD) of the outer loop.

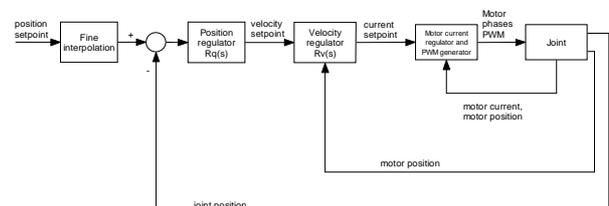


Figure 12. Joint servo control

Finally, if a joint torque sensor is available, it is possible to consider using a modified torque-disturbance observer [9] that helps achieve both benefits of LB and LD design in a single scheme: it allows a large-bandwidth motor-control loop, without affecting the

damping of the load. It is however unlikely that the DELIAN joint can afford a torque sensor, therefore this solution is not proposed as baseline.

A servo controller has been utilised and preliminary tuned for the joint EM, implementing the dual-loop control scheme in Fig. 12. Velocity and position loop responses are shown in Fig. 13 and 14.

It can be appreciated that when only the motor velocity loop is closed, the motor velocity is well controlled while the load exhibits oscillations, due to joint flexibility. The load oscillation is damped when the outer joint position loop is closed around the inner motor velocity loop, showing the benefits of the dual-loop scheme.

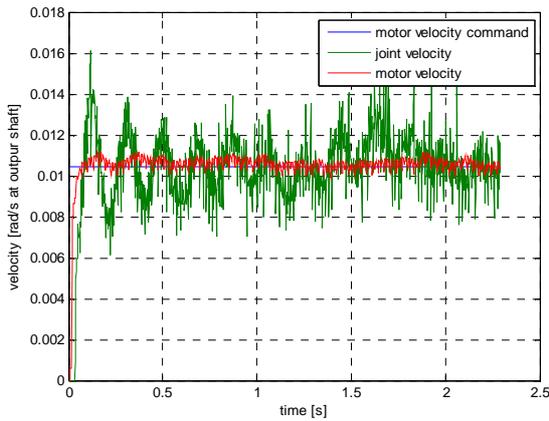


Figure 13. Motor velocity loop response

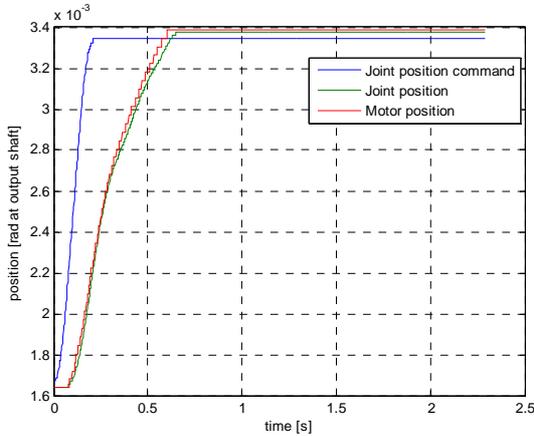


Figure 14. Joint position loop response

This preliminary tuning is already an acceptable trade-off between steady-state and dynamic performance. The unloaded joint has an average accuracy of 0.024 deg and an average repeatability of 0.005 deg. These values are compatible with the accuracy/repeatability budget allocated at joint level.

5.1.2. Deflection compensation

Arm deflection compensation will play an important

role in achieving the required positioning accuracy. Two methods are envisaged: model-based deflection compensation and vision-based control.

In most missions a camera will be available either mounted on the arm or on the platform, so that vision based control is a feasible solution. However, for the purpose of the DELIAN project, it is valuable to exploit a model-based compensation, either with or without the help of deflection sensors in the arm. Two possible solutions are considered:

- off-line correction of the commanded pose (a fake-pose-like method), as employed in [8];
- on-line integration of deflection compensation and inverse kinematics (Fig. 15).

The former is a simpler method, requires less computational resources and is compatible with an explicit inverse kinematics based on a pure rigid model at the inner layer. The latter requires more computational resources but could lead to improved positioning accuracy, especially for long slender arms.

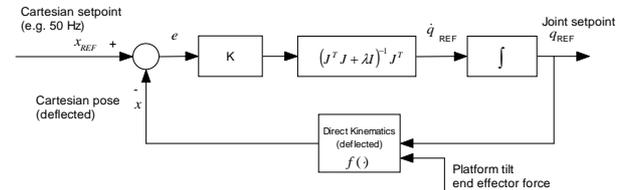


Figure 15. On-line deflection compensation

The steady-state solution shown in Fig. 15 correctly accounts for deflection compensation if the feedback branch includes static deflection effects. The Jacobian matrix J can be obtained analytically or numerically via differentiation and it can be based on the rigid model of the arm. An inverse kinematics based on a damped least-square inverse Jacobian is preferred but a transpose Jacobian could be also employed.

5.1.3. Dynamic control of arm flexibility

For long slender arms, also the dynamic vibrations induced by flexible modes are important. This is why the study includes the assessment of a method for active control of flexible modes. Different techniques have been proposed and investigated by the research community.

An interesting method suggested for DELIAN is Wave Based Control [10]. The idea underlying this method is very simple: energy and momentum enter and leave the flexible system (i.e. a DELIAN limb) at the interface to its actuator (i.e. a DELIAN joint). The motion within the system propagates simultaneously in two directions, from actuator to the free-end, and back again. The Wave Based Control interprets the motion induced by the actuator into the flexible system as the sum of two components: an outgoing and a returning wave.

The key to the control technique is to identify the returning wave (e.g. by measuring it at the interface)

and to move the actuator in just the right way to “absorb” (cancelling) the returning motion, thereby actively damping the vibration.

Another method under study is the one proposed in [11], employing a model of the distributed flexibility of the links based on a floating frame-of-reference technique.

5.2. Ground Control Station

The DELIAN GCS will provide capabilities for full arm-ground command and control, telemetry data processing and data dissemination to the scientific team for mission operation support.

Based on the applicable requirements, the following capabilities can be summarised for the GCS:

- Accept and transmit user commands to the OBC, receive, process and visualise telemetry;
- Provide a virtual environment, where command sequences can be simulated and rehearsed;
- Enable different operation modes, including remote control and automatic mode;
- Support robot program preparation (activity planning);
- Support arm control parameter tuning, joint and arm calibration, and test;
- Support science data monitoring and simple payload control.

A functional diagram of the GCS is shown in Fig. 16.

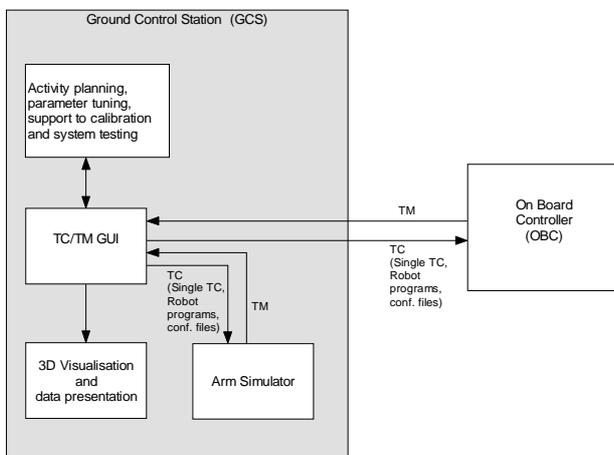


Figure 16. Ground Control Station functional diagram

6. CONCLUSION

An overview of DELIAN project has been presented, showing the system design process and the main results achieved. The activity performed so far includes the development of a compact and lightweight joint, selected among the identified joint families which will be used as building blocks for the arm. Control design aspects are addressed, showing the adopted solutions for joint servo control and arm control at Cartesian level.

Next scheduled activities are the completion of joint testing and the detailed design, development and testing of a full robot arm (DELIAN DM).

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