BI-STABLE SHAPE MEMORY ALLOY SHUTTER MECHANISM DEVELOPMENT AND TESTING

Matti Häberlein (1), Reiner Barho (2)

(1)Airbus Defence and Space, Email: matti.haeberlein@airbus.com
(2)Airbus Defence and Space, Email: reiner.barho@airbus.com

ABSTRACT

In the frame of the development activities for an optical instrument, unconventional shutter mechanisms were sought-after.
Starting in early phases of the study, the paper will contain an overview of some trades which were performed to identify the most suitable solution.
Following that, the selected design of a bi-stable shape memory alloy driven shutter mechanism will be presented and discussed.
Including a recapitulation of the chosen design development and verification (DDV) approach, followed by attention on the complex assembly integration and test processes, the paper will outline additionally some perspectives regarding begin- to end-of-life performance predictions of these actuators and verification methods in specific life tests.
The paper closes with a conclusive statement of the present achievements on this type of shape memory alloy driven mechanisms in the frame of the study and further perspectives for usage of the presented technology in future mechanisms.

1. INTRODUCTION

The related instrument is an optical working system with two channels for radiometric measurements. As depicted in Fig.1 the instrument consists of an optical bench (OB), equipped witch two optical channels implemented in the bottom compartment.
On top of the OB a housing for electronic devices is mounted which provides a lateral slot for the shutter mechanism. The whole assembly is covered with an electronic box on top, which provides power as well as a data handling device, to assure stand-alone functionality of the instrument.
The shutter mechanism for the optics is thus made of two basic assemblies, namely the stator parts which are the mechanism base plate, containing the actuators and the surrounding structure, as well as the brackets for the drive shaft and the launch lock for the covers.
The other assembly is combined by the rotary parts, i.e. the flaps which are covering the baffles of the optical channels and a bridge which assures a combined movement of these flaps during actuation of the mechanism.
The main task of the mechanism is to cover the optics for calibration purposes in the closed state and to open the optics for detection duties of the instrument.

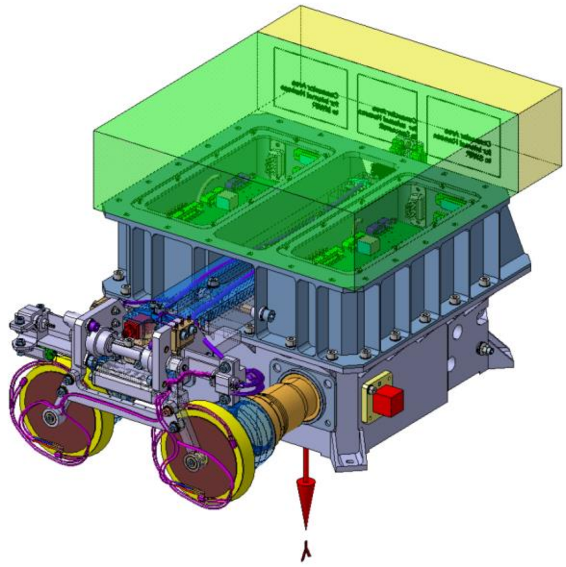

Figure 1. Optical Instrument equipped with shutter mechanism

As to be in line with the needs of the field of view and to protect the optics against obscure and coverage in the line of sight during the earth view, the mechanism was designed for being able to open rotatory 105°deg around its drive axis.

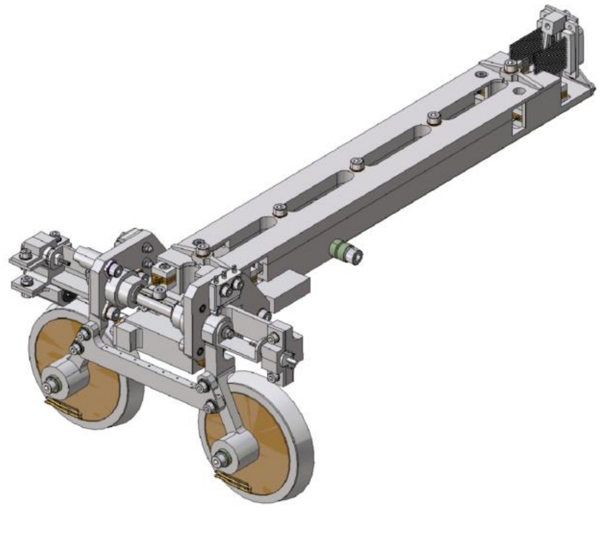

Figure 2. Shutter mechanism in closed status, shown without harness & MLI

The actuation of the rotatory movement is realized by a joint solution whereas a dyneema rope is wrapped

Proc. '16th European Space Mechanisms and Tribology Symposium 2015', Bilbao, Spain, 23–25 September 2015 (ESA SP-737, September 2015)

around the drive shaft and linked to a linear shape memory actuator which is placed in the lateral baseplate. As actuator a Nickel Titanium (NiTi) wire shape memory material is used in an agonistic-antagonistic principle and trained for the specific duty.
Shape memory actuators (SMA) are using the “memory effect” of its original shape. The latter means that the alloy which is deformed in a cold condition can reform itself to the original shape when up-heating of the structure is applied.
This kind of behaviour is based on phase transformations from austenitic into a martensitic arrangement, respectively a twilling and de-twilling of the certain crystal lattice in the martensitic state.

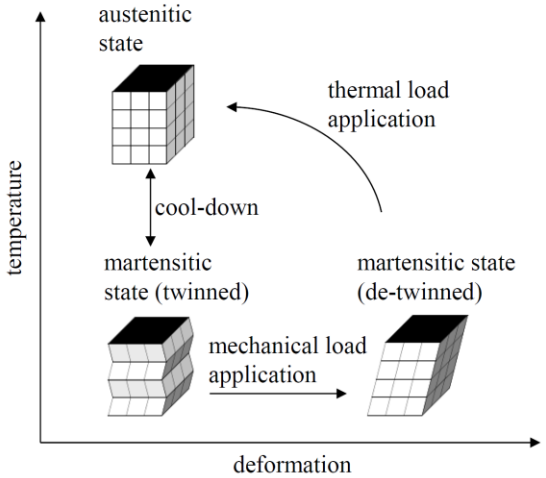

Figure 3. SMA effect - state diagram

Mechanical forces and movements can be evoked with such an alloy by generating a temperature and/or tension related change of the shape, respectively the volume.
Thus, a comparison with bi-metals would apply whereas the energy capacity of the shape memory alloy is about one magnitude of order higher than of bi-metals on similar temperature level [1].
Generally the shape memory effect can be distinguished between a pseudo plastic and pseudo elastic behaviour, what means that the type of retransformation is of differential motivation and in case one, based on an intrinsic transformation process, whereas in case two the retransformation is evoked by extrinsic matter. Hence, in the here used effect the second type was identified as the right solution for the purpose due to the need for re-actuation and transformation from external source.
Regarding the needs of the application, the shape memory effect was used as agonistic antagonistic pair of actuators in a flip flop drive principle.
This principle is based on the fact, that the alloy can be pre-strained by a certain mechanical load which is in general much lower than the force generated by the shape transformation during up-heating. This kind of phenomena is directly linked to the pseudo plastic SMA effect, which is used for this type of actuator since the enthalpy difference between the phase transformation from martensitic state into austenitic state and subsequent down cooling to a twilled martensitic crystal lattice, is much less in comparison with the force needed to de-twin the latter into an ordered martensitic array, by application of an external mechanical load.

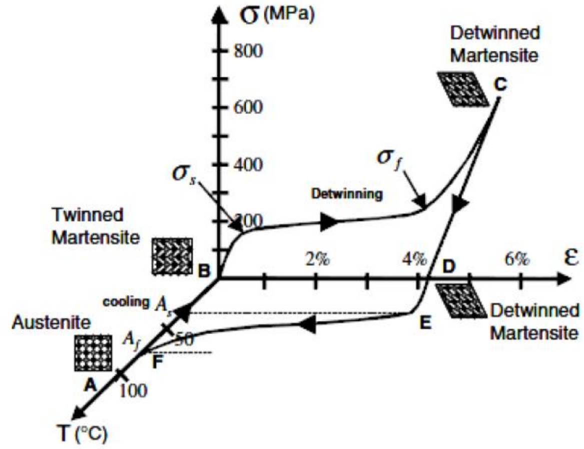

Figure 4.Principle of the pseudo plastic SMA effect [2]

Since this delta exists theoretically in a range of ~4% strain of the original actuator shape, it can be used as flip flop switch between the two actuators, whereat one of the both players is in state number one (martensitic twilled) whereupon the other player is in state number two (martensitic de-twilled), evoked by each other, due to an up-heating of one of them and vice versa.

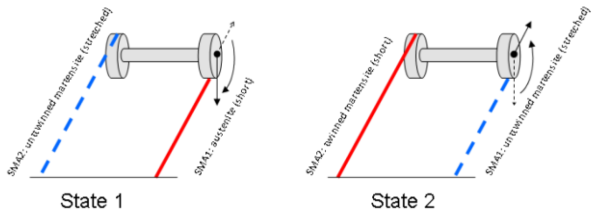

Figure 5. Agonistic-Antagonistic actuator principle schematics

In general, when the pre-strained actuator what we call the agonist and which – at the beginning is at state one – is powered, it pretensions its antagonist from state one into state two and the principle remains for being actuated the other way around as well.

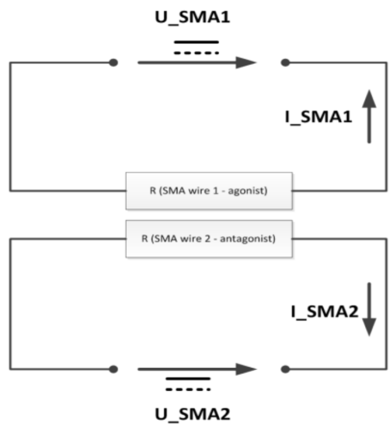

Figure 6. Usage of the actuator as heating element

The up-heating itself is generated by using the wire as an ohmic resistor in a circuit. This approach saves on the one hand the usage of additional heaters in the mechanism and offers on the other hand a valid possibility to trace electrically the overall condition and status of the wire, e.g. in case of failures, crack or any other anomalies that may occur during mission.

2. MAIN DRIVING REQUIREMENTS

Regarding the special kind of this shutter mechanism for the above introduced instrument, a bi-stable system was required since the shutters are obliged to remain in its open or closed position when the mechanism is turned off (un-powered open / un-powered closed function).
As functional main driving requirement, the time consumed for opening and closing the flaps was specified to less than 15 seconds while consuming power off less than 2,5W during the mechanism operation. Furthermore a main driving requirement with respect to the feasibility of the mechanism actuator was the magnetic moment, which was identified as a constraint coming from the platform and prohibiting in fact the usage of common motors for the shutter mechanism. A conservative approach with a motor design was additionally blocked due to the weight, cost, power and failure mode requirements of the instrument.
Regarding the functional and design aspects as well as with respect to the complexity of the mechanism the specification of independent and tightly controlled up-heating possibilities of the both flaps was considered as a basic constraint, in addition to the detection of the shutter status. Both criteria induce a higher complexity of the system since the up-heating functionality requires an additional slip ring application, whereupon the detection requirement states a basic need for micro switches to be implemented in the kinematic chain of the mechanism, what induces in turn additional resistive moments on the torque budget.
Other main driving requirements were the geometry and dimensional constraints of the mechanism compartment within the instrument, the testing under 1g and 0g conditions which induced additional need for an anti-gravity rig and as well the overall need for a lunch locking device to be applied as holding element of the rotatory parts.

3. PREDEVELOPEMENT STUDIES

At the beginning of the study some basic investigations on the actuator and the feasibility of the agonistic-antagonistic principle were made. A simple test bed is described in *Figure 7* in which the two SMA players are linked to a force measurement box and could be powered independently to investigate the force which is needed for a re-straining of each of them, by powering the other. The outcome of this pre-investigation was a first knowledge regarding the very basic behaviour of the actuators in such an arrangement.
Furthermore, some basic studies on correct usage and application of the SMA wire within a circuit could be made with this set-up.

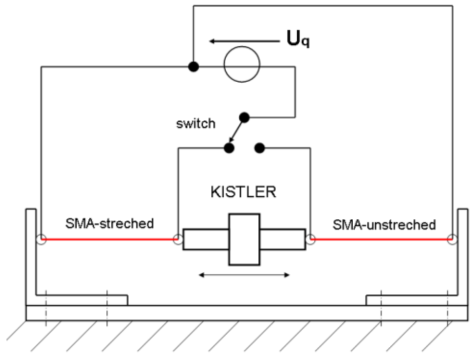

Figure 7. Agonistic-Antagonistic actuator principle

Additionally, the transformation temperatures and forces and thus, the basic characteristic of the actuator could be investigated in general.
As a second step, the set-up for a simple hinge was developed and was in consequence build up as a first demonstrator for the principle of a mechanism which could open or close a shutter with flaps.
In this set-up the two SMA partners were mirror-inverted wrapped around a common shaft, whereat the one was tensioned mechanically to a martensitic de-twinned state whereas the other was down cooled to a martensitic twinned state to be de-twinned by the phase transformation of the first wire.
The outcome of this demonstrator was the correct application of the actuator principle to a rotatory system. Thus it could be demonstrated with this model, that at least a 20.000 cycles in a flip flop movement of 90° is possible. Although the end stop was hold by a magnetic device and thus the actuator had just to pull the shutter from one stable position into the other.

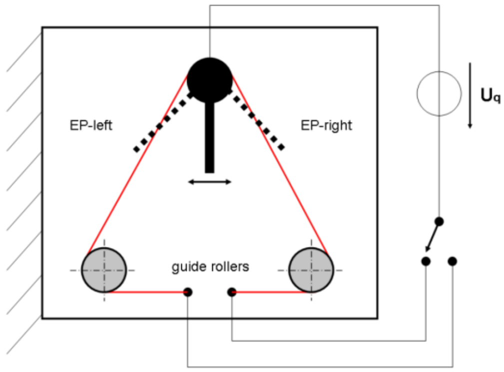

Figure 8. Agonistic-Antagonistic actuator hinge

As a further basic investigation in the frame of this predevelopment, the degradation behaviour of the shape memory effect over the cycle amounts was examined and compared to existing literature values. The major outcome of these considerations was in fact, that with an un-trained wire batch, a degradation of the memory is resulting in the magnitude of about 50% after at least 5000 actuations. Hence the generated force and stroke was reduced upon half the initial value. With a trained wired batch, the effect remained almost on the pre-trained level.

Since the SMA effect is regressive over a certain amount of transformation cycles, depending from actuation parameters like power introduction time and magnitude, as well as geometrical factors and mechanical constraints (e.g. stress and strain at the integration status), the level of the effect which can be used at end of life (EOL) shall be stable in a way that no further degradation is considered at actuating the drive at EOL performance. Hence the SMA has to be pre-trained prior implementation, to overcome the degradation phase of the material and get to an effect level where the shape memory can be used on a likely stable plateau.
As conclusion of the pre studies it figured out, that the transformation process is regressive over the first 5000 cycles in the frame of the considered use and geometry of the actuator. Additionally it was identified as outcome of the pre studies, that the material degrades in two magnitudes of order faster, when transforming the alloy under geometrical constrains in terms of pulling against end stops or other highly resistive limitations.

4. CONCEPTS AND TRADES

Based on the outcomes of the pre studies some concepts and trades for an application of the flip flop switching in a shutter mechanism were performed.
At first, a batch of concepts for mono stable shutters were faced as well since the specification of the bi-stability was not hard fixed from the beginning of the study. In the frame of the need for a bi-stable shutter which was identified clearly after the requirement review for a bread board, the concepts were limited to this purpose and trades were considered for the design of a first technology demonstrator subsequently.
The relevant trades were performed between different design approaches with and w/o balance masses on the rotation axis on the one hand, and on the other considering the usage of a launch lock, in combination with balance masses and additionally the implementation of a notch with respect to a locking of the end stop position. Furthermore the impact of turnaround rolls in the actuation chain were investigated and compared to a solution with no redirection of the actuator wire within the baseplate were regarded as well. Finally a technology demonstrator was build-up of a 3D print model with representative bearings, rope application and aluminium shaft. This demonstrator used the pre study design parameters for the actuator, was equipped with a shutter dummy and executed 30.000 cycles of actuation under laboratory conditions in 1g successfully. The chosen trade solution for this demonstrator was an unbalanced inertia on the drive axis and with turnaround rolls for 180° redirection of the wires.
The main finding on this model was the correct termination of the wire and transmission of the lateral contractive induced movement over a simple mechanical connection to the rotatory shaft. Furthermore, on this model it could be investigated how the agonistic-antagonistic concept can be applied to a bi-stable shutter mechanism without using an extra holding device (magnets, springs, notches etc.) in the end stop position, however in addition, that the end stop position cannot be kept stable in principle due to the fact, that if the agonistic SMA is powered, it indeed pulls the antagonistic SMA from the twinned into un-twinned state, but it lasts an elastic share in the phase transformation, what is inducing in turn, a backlash in the rotation of about 20° on the shaft.

5. MECHANSIM DESIGN

With the earned knowledge of transmitting the lateral actuation by use of the adequate SMA termination and electrical connections, the design for an elegant bread board was set up and was further pushed to an early engineering and qualification representative model (EQM), that is introduced as overall output in the frame of the study and was functional tested under laboratory conditions up to now.
The overall mechanism weight of the EQM is approximately 1kg and the main dimensions are about 350mm by 150mm. The actuator which is used in the final design of this model is a wire of NiTi which consist of 55,9% Nickel and 44,07% Titanium amount and is electrically acting as resistor to be up heated by powering the circuit using 5V DC at 1.4A per SMA wire under laboratory conditions.

1.1. Main Structure and components

The main structure thus consists of a baseplate which carries the SMA actuators with termination sliders and a dedicated cover for these parts.
At the front side of the main structure is the rotatory assembly installed and carried by two brackets, which serve as the bearing housing on the one hand and as holder for the slip rings and the micro switches on the other hand. Directly beneath the drive shaft is the launch lock attached to the bottom side of the base plate, so it can fix the flaps in closed position during launch, acting as a pin puller in lateral direction as subsequently described in section 6. The main interfaces of the mechanism are two screw joints in the baseplate for mounting from the top side and two additionally joints, which connect the mechanism laterally onto a pair of equidistant ribs in front of the mechanism compartment surrounding slot of the instrument structure.
As the mechanism is obliged to be thermally decoupled from the surrounding instrument, all interfaces on the baseplate to the instrument are equipped with thermal washers, whereas the structural parts are polished to protect the SMA wires from unintentional up heating and uncontrolled actuation. The power and signal connection is given by an electrical interface with two connectors which are mounted in a connector bracket on the rear side of the baseplate and carry all harness endings for power and signal transfer from and to the instrument in main and redundant circuits. One of the main purposes of the baseplate is to provide a well-designed tube channel with dedicated thermal surfaces

to sustain the proper cool down of the SMA wires as calculated beforehand in simulations. These channels are implemented between the baseplate and the cover structure.

1.2. Rotatory assembly and actuation chain

With the goal of being bi-stable and powered off, in closed and open status, and additionally to avoid further resistive in the end stop, the backlash which was identified during the predevelopments was covered with a free wheel implemented in the shaft assembly.
The latter causes a sectioned drive shaft assembly on which the SMA stroke is transmitted onto the free wheel by a rope and further from the free wheel rotatory with a pin over two guiding shafts on each side.
Whereas the guiding shafts are supported by an O-configuration of respectively one angular ball bearing pair in each mounting, they are linked to each other via a bridge system with a support for the shutter flaps and are connected to the free wheel with radial ball bearings.
With respect to the power and signal transmission of the thermistors and heaters on the flaps, dedicated slip rings are placed in the rotatory shaft assembly at the side and connected via a driving pin.

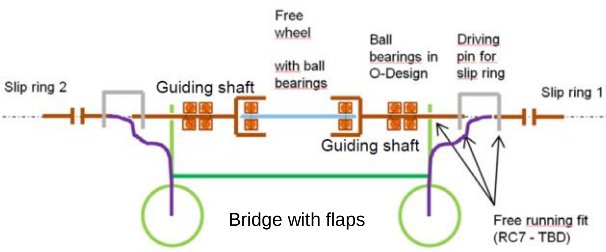

Figure 9. Design concept for the drive shaft assembly

The design of the drive shaft assembly is principally affected by the application of the free wheel within the actuation chain due to the fact that the backlash has to be considered as additional dimensioning element of the actuator since the respecting circumference must be added to the overall actuator length.
Furthermore the end position of the cover is fixed by an internal holding element since the actuation is decoupled via the free wheel from the drive shaft but on the other hand linked to the backlash rotation over the inner ball bearings. The holding functionality was implemented in the design by using the over travel and switch holding force at the micro switches in the end position to get the rotatory parts fixed in the open and closed state independently from the actuator backlash.
The drive shaft assembly, as the key element of actuation transmission is composed in the final design of the free wheel, on which the ropes of the linear SMA actuators are wrapped around in dedicated grooves and fixed with a joint termination in the middle of the shaft.
This element is linked via the ball radial bearings to the outer guiding shafts which are equipped with the angular ball bearings in O-design with 15° contact angle and placed back to back in a hard mounted configuration.

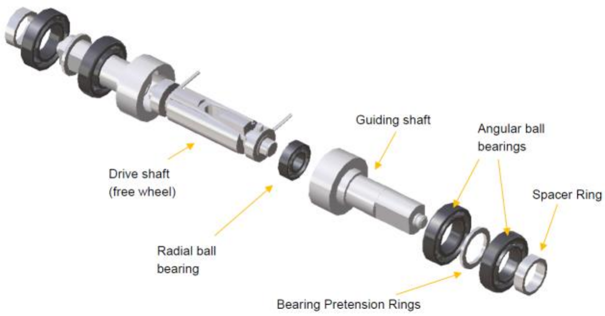

Figure 10. Overall shaft assembly

Chosen radial ball bearings are GRW miniature bearings of the type GRW-SV-685 NG THB B-1724 L103 CP. The angular ball bearings are of the type GRW-SV-789 C P4 TA B-1724 L103 CP.
The pretension of the bearings which was chosen as to be 10N is applied via the spacer ring and the lever hinge of the bridge assembly, by fixation with the slip ring coupling with a self-locking screw.

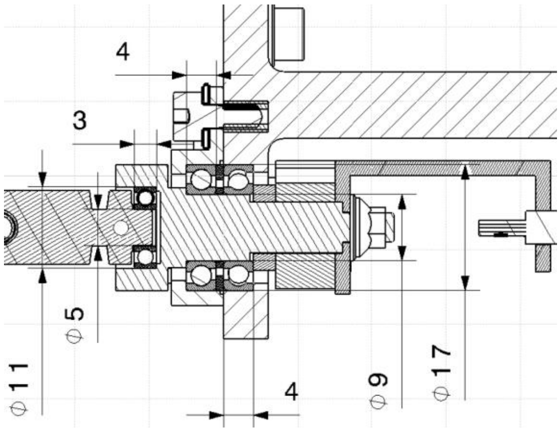

Figure 11. Sketch of ball bearing assembly on guiding shaft and drive shaft

Other functional components of the rotatory assembly design are the heaters on the shutter mechanism covers which are made of polyimide kapton layers and tailored to the ring on ring geometry of the area to be temperature controlled at the covers. The warming and cooling control loop is set up with the described heaters and using additionally three PT1000 thermistors for majority voting to be controlled by free programmable gate array (FPGA) based device within the electronic box of the instrument.
As a signal giving trigger for detection of the end positions, Petercem micro switches type T6932 are used in terms of feedback for the shutter status. The detection is realized by over travel of the roll contacting element with a notch on the shaft. Thus the switch is together with the slip ring also used to introduce the mentioned holding force for a secured closed or opened state after shutter actuation. For power and data transmission over the hinge a micro slip ring with 12 channels and low resistive was implemented in between the rotatory system and the main structure.

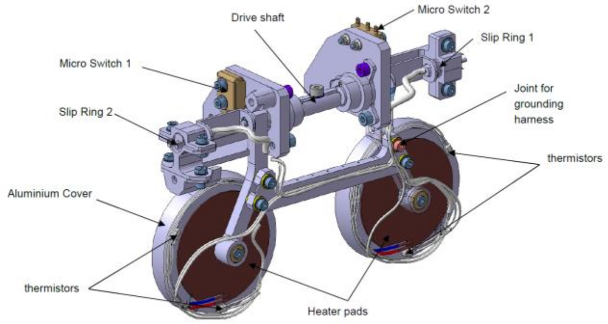

Figure 12. Rotary parts of the mechanism with mounting brackets

1.3. Redundancies

The concept for the overall redundancy of the shutter mechanism implements a redundant SMA wire on the actuator as well as on the launch lock. These redundant wires provide a general cold redundancy of the drive of the mechanism as they run in slack mode within the functional chain under nominal operation and can be activated in case of a failure of the main actuators.
Furthermore, redundancy is implemented in the heater circuits on the flaps. A reduced failure detection and recovery analysis was performed in the frame of the study as well and showed well suitable robustness w.r.t. any failure in terms of wire crack or overheating the SMA's, respectively other anomalies in the main actuation chain.

6. LAUNCH LOCK DESIGN

The launch lock of the mechanism is placed on the bottom side of the baseplate beneath the drive axis, where it can act as a pin puller, blocking one lever of the flaps with a holding pin during the launch sequence. The actuation is again realized by a shape memory wire which comes from the same batch as the drive actuators and is as well implemented as main and redundant system by using an additional SMA in slack idle mode during nominal operation.
The launch lock SMA actuator thus, is pre-tensioned by a spiral spring which pushes the pin in a dedicated hole on the lever arm at the bridge system, securing the overall rotatory assembly for the locked status during launch. By powering and up-heating the actuator, the wire pulls the pin out of the hole against the spring force, whereas a secure pin which is guided by a lateral groove in the locking pin snaps into a saving hole, where it fixes the unlocked position for free operation of the shutter mechanism.

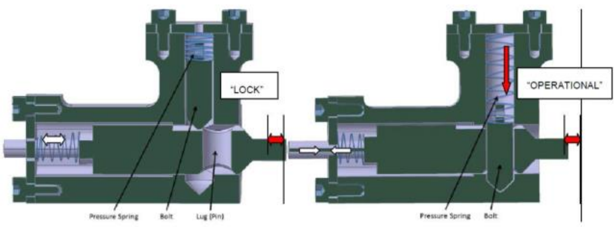

Figure 13. Operation principle of the launch lock device

The launch lock can manually be reset by a lacing cord which is attached to the secure pin and pulls the latter at a reset execution into the lock position against its bias spring, that pushes in turn immediately the locking pin back into the saving hole due to the pretention of the SMA actuator by the bias spring of the locking pin.

7. DDV APPROACH

The chosen design development and verification (DDV) approach for the mechanism was based on the decision to verify all critical parts on component level first and to test it afterwards in combination with the overall mechanism assembly in dedicated functional tests prior to a life test. Vibration and thermal vacuum (TV) tests were not foreseen to be performed on mechanism level as preliminary analysis results showed that the behaviour of the mechanism in both cases but mainly in the TV test is highly depending on the surrounding environment and the arrangement and fixation in the instrument. In contrary to a life test on scanning or pointing equipment wherein the bearings or related equipment are considered mainly as the most critical subsystem, the purpose of life test on this shutter mechanism was to verify the EOL performance of the needed actuator stroke and pre-calculated degradation level from begin of life (BOL) performance. Thus the actuator was implemented in the technology demonstrator model and run a performance test over the amount of 30.000 cycles whereat the track and force of EOL actuation was measured.

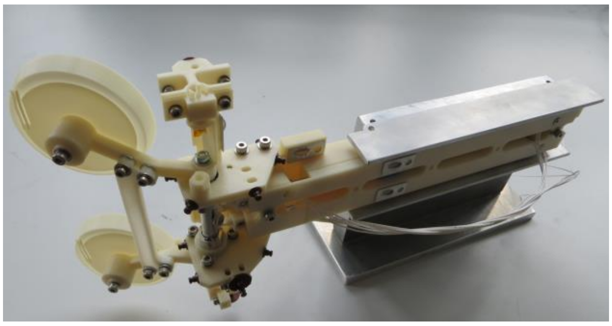

Figure 14. Bread Board for functional testing

The tests on component level which were performed well in advance of the overall functional testing included the verification of the ring on ring heater power budget and the proper function of the slip rings as well as pretension tests of the bearings with additional friction torque measurement in preloaded and mounted configuration. Furthermore, some investigative testing of the actuator dynamics respecting the up heating and down cooling rates under vacuum environment, in relation to pre-simulated values was performed, to get early knowledge of the behaviour in a potentially following TV test campaign.

8. TESTING

The tests related to the actuator behaviour under

environmental and different load application conditions were initially of great interest since it represents the core investigation of the overall study facing a later functional EQM which shall be tested in a TV test campaign as preparation for further studies.
Therefore the actuator was simulated using a MATLAB/SIMULINK® model of the virtual specimen in a representative virtual thermal environment and the outcome of this down cooling rates were compared to the measured data which were produced in the real SMA actuator test bed in the vacuum chamber.

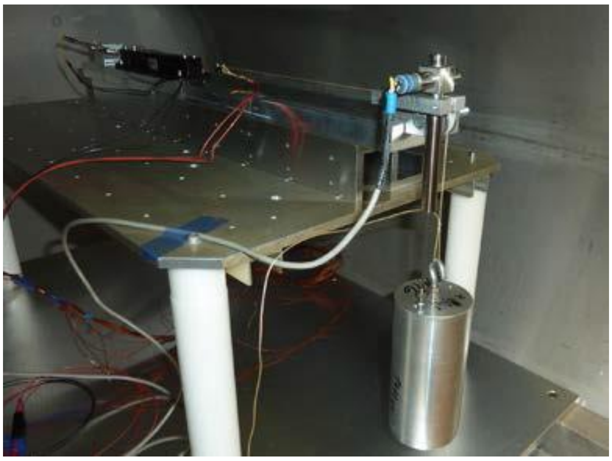

Figure 15. SMA actuator TV test bed

The test bed for the actuator was composed of a table with a mounted black aluminium bracket to provide an adequate radiative environment in a channel for the SMA guidance. A turning roll on a balcony guided a rope to a representative load which could be applied as hanging mass. The actuator was powered then and the stroke and resistive as well as the temperature of the wire was measured.
As the simulated cool down of the wire was calculated with 320seconds and the cool down curves of the SMA power characteristic tests identified a similar time range for the actuator, the model was identified as an adequate tool in terms of designing correct actuator dimensions with respect to the surrounding environment respectively.

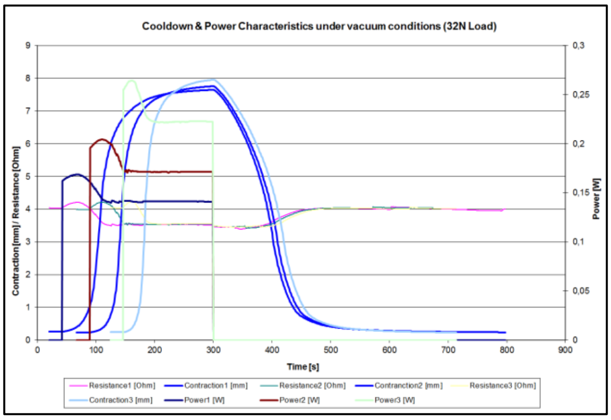

Figure 16. SMA power characteristics in TV conditions

As second critical field for intensive pre testing activities a batch of trades were identified to be tested for the most suitable SMA wire termination.
This connection should be able to sustain the actuator force transmission over the whole actuation cycles and furthermore being thermally and electrically decoupled in the section between the actuator and the drive shaft. The latter was obliged to be designed with a slider block made of an electrical neutral material, where the SMA wire is crimped in from one side and a dyneema cord is applied from the other side, so that the transmission of the lateral actuator force to the rotatory drive shaft is ensured by the wrapping of the cord around the shaft with a joint fixation as final termination.
Hence, the described actuation chain was tested with different termination methods, e.g. with a knot between the wire and the cord as one solution and some crimping methods as additional approach. Gluing solutions, welding and soldering were also investigated but failed.
Finally, all tests showed that the crimped termination of the actuator has the most advantages and provides the highest reliability in terms of mechanical connection failures. The functionality of the launch lock concept was initially pre tested in a simple 3D printed bread board (BB) of the component and later verified on the EQM launch lock. In a first run, 50 cycles were tested successfully without any performance anomaly. Then 100 release cycles were successfully tested as well.

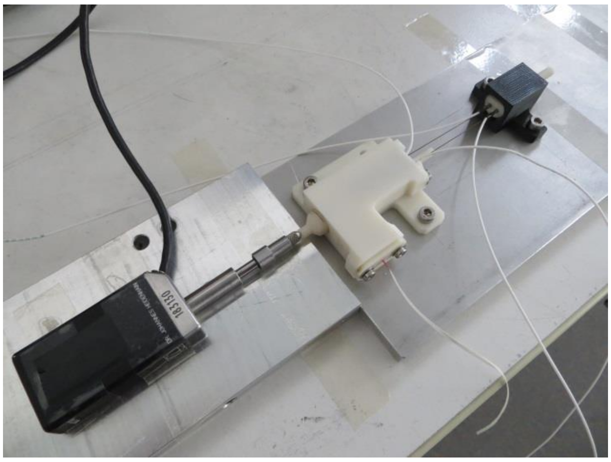

Figure 17. Launch Lock BB release test setup

All mounted on a test bed baseplate and pushing/pulling against a Haidenhein high precision linear measurement device the nominal current and tension on both SMA were applied for 5 seconds each and manual re-setting by the lacing cord on the secure pin. The similar test was performed subsequently with the EQM launch lock device what showed the same performance.
The pretesting of the bearings was performed after adapting the bearing assembly inner pretension ring for application of the 10N pretension. The preloading was executed on a dummy drive shaft with representative tolerances and with mounted angular ball bearings. A load cell was placed beneath the drive shaft and a pressure sleeve was applied for load introduction. 4142,6N/mm was identified as mean stiffness of the

bearing over a set of 30 preloading executions whereas a preloading gap of ~2,4µm resulted and was applied by adaption of the inner pretension ring

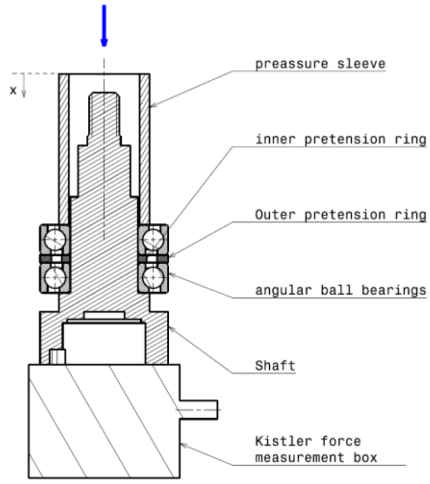

Figure 18. Ball Bearing pretention test setup

After correct application of the preload through adaption of the inner pretention ring thickness, the both angular ball bearings were integrated together with the radial ball bearings onto the drive shaft and into the bearing housing brackets and friction values off the whole bearing assembly were measured for validation of the torque budget.

9. SUMMARY AND CONCLUSION

In the frame of the study a predevelopment for a bi-stable SMA driven shutter mechanism was performed. This development was mainly dedicated to the possibility of using a simple SMA wire as a dynamic actuator instead of the well-known application in a single shot device and investigating the performance over a dedicated mission time facing at least 20.000 actuation cycles.

The latter resulted in a batch of lessons learned subjects in the field of the coupled "thermos-electro-mechanical" behaviour of directly powered SMA under vacuum conditions, as well as regarding termination techniques of the actuator, but mainly in an area with respect to the proper application of the memory effect training due to a well suitable prediction of the correct EOL performance and related degradation of the usable transformation magnitude in an SMA actuator of NiTi, with pseudo-plastic characteristic.

Hence, beyond the predevelopment an early BB was build up as technology demonstrator and successfully functional tested for the relevant need of actuation cycles under laboratory conditions.

Based on this success, an elegant bread board with EQM design trades was manufactured as a successor of the demonstrator and also functional tested under laboratory conditions.

Finally, an EQM model was build up and integrated under cleanroom conditions and first functional tests verified the possibility of driving the shutter mechanism with the assumed BOL torque from the SMA actuator.

The main lessons learned refer to the robustness of the torque margin at EOL, which could not be achieved sufficiently with the EQM model due to design constraints that caused higher degradation behaviour of the SMA as preliminary assumed and tested with the predecessors of this model and related mainly to the kind of over travel of the chosen switches.

Conclusive, in a consequent manner of reaching the predicted torque margins at EOL in the actuation chain, a re-design of the drive has to be implemented in the next phase and tested.

Therefore, the model will be equipped further on with a more extended SMA actuator which is trained in advance to EOL performance facing a reduction to zero of the memory degradation with the goal to reach the similar actuation performance over the 20.000 cycles with positive torque margin in the EQM as well and performing after this modification a successful environmental test campaign for further qualification.

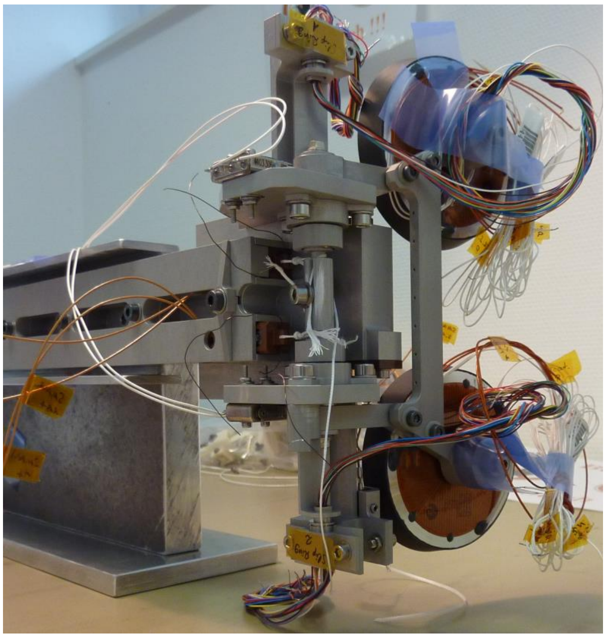

Figure 19. EQM model in integration rack without MLI

10. REFERENCES

1. Schiedeck, F. & Wallascheck, J. (2009) *Entwicklung eines Modells für Formgedächtnisaktoren im geregelten dynamischen Betrieb*, © PZH Produktionstechnisches Zentrum GmbH, IDS, Gottfried Wilhelm Leibnitz Universität Hannover, GER, 17-20

2. Dimitris C. Lagoudas (2008) Shape Memory Alloys Modeling and Engineering Applications, In *Introduction of Shape Memory Alloys* (Eds. P. K. Kumar, D. C. Lagoudas), DOI: 10.1007/978-0-387-47685-8 1, © Springer Science+Business Media, LLC 2008, pp 18-68