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# Kinematic Solution for a highly adaptive Droop Nose

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**Abstract**

Keywords: Morphing, adaptive aircraft, system design, kinematics, actuation systems, laminar wing, optimization tool

In this paper a kinematic solution for a highly adaptive droop nose of a single aisle passenger aircraft is shown and its development process explained. The solution presented was developed and built in the framework of the EU (FP7) project SARISTU. At the end of the project a wind tunnel test and a life-cycle ground test of the enhanced adaptive droop nose (EADN) will be performed. The aim of this project was in part to develop an unslotted droop nose skin without any gaps and steps. The kinematics described herein is considered as an enabler-technology for laminar wing flow. The kinematics ensures an adaptive high lift configuration of the unslotted leading edge, by internally deforming the skin. In the first part of this paper the kinematic design process is highlighted and an in depth exploration of optimization parameters for such a system is made. A main objective was to achieve the targeted deformation shapes with a low complexity actuation system which fits into the extremely limited available space. Special note for the design process had to be made of the large deflection vs space allocation ratio. To simplify the actuation system, simultaneous and uniform deployment of all differently sized kinematic stations is required which added further complexity to the kinematics design. The second part of this paper deals with the complete kinematic system for a wind tunnel test setup. Its functionality is described and the detailed design is shown. Thirdly a comparison is made with a previously developed kinematic system (FP7 project SADE) and scalability effects are explained in some detail. In particular the reasons why despite similar geometries almost a complete redesign was necessary are discussed. The work described in this paper shows the robustness and flexibility of the developed design tools and highlights the technological readiness of kinematic systems for morphing structures.

## 1. INTRODUCTION

With regard to the ACARE Vision 2020 and Flightpath 2050 work has been ongoing to reduce the $CO_2$, NOx emissions as well as the noise footprint of commercial aircraft [1][2]. Based on these goals one attractive option is to develop technologies to realize natural laminar wings, which promise a 6% drag reduction. This directly impacts the fuel consumption and has the side effect of decreasing the airframe generated noise by eliminating slat noise which is a major contributor in approach For a natural laminar wing several hurdles have to be taken, especially with regard to skin-smoothness, as any unevenness can

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lead to a laminar-turbulent transition. Looking at a state of the art wing today most dominantly in the area of the leading edge several clear gaps- and steps related to part of the high-lift system, the slats, can be seen. One option is to create an adaptive droop nose, which is a fully integrated part of the wing and not a separate structure as today [5][8]. To make this possible the skin in the leading edge has to be flexible enough to allow for large deformation to still enable a deployment of a high-lift device [6][7]. In the FP7 project SARISTU activity stream *"AS01 Enhanced adaptive droop nose for a morphing wing"* under the lead of DLR this idea is examined in great detail not only with regard to a morphing wing leading edge (LE) but also taking into consideration to integrate typical LE functions like bird strike protection (SONACA), de-icing (GKN), surface and lightning protection (AGI, GKN) [3]. Additionally the manufacturing and industrialization of the concept was another focus in AS01 (Invent GmbH, VZLU, AGI).The work described herein focuses on developing a low-complexity and lightweight actuation system for the droop nose, working hand in hand with all partners to achieve a fully integrated morphing solution. Work on an adaptive droop-nose kinematic actuation system started in the previous projects InHiD (LuVo IV) and SADE (EU-FP7) [4]. In these two projects the feasibility of such a system was demonstrated.
The development of the mechanical kinematic system for the SARISTU project consisted primarily of optimizing the system in terms of weight, scalability and complexity. The baseline for this development was the experience gained in the previous FP7 project SADE. In the SADE project 3D and scalability influences were not considered, as the SADE airfoil was simply an extruded 2D wing section. Also the kinematic system in SADE was not optimized for weight and complexity. Other issues like maintainability and industrialization of the product were also not considered. In the following paragraphs an overview is given first on the geometrical design criteria and optimization, followed by a detailed design of the kinematics. Concluding a comparison between previously developed systems and the new design is made.

## 2. Kinematic actuation system design

The kinematic designed is foremost influenced by the required deformation and the target shapes. Based on the cruise shape of the wing and the drooped (high-lift) shape hinge or load introduction points for the different kinematic stations can be derived. These points describe a movement-curve for each kinematic station. Based on the skin-requirements (e.g. waviness) the number of these points for each station is determined. For the WT-test section of the airfoil two points per kinematic station are considered to be sufficient according to relevant research performed by DLR. With the definition of these points and their corresponding movement curve a kinematic system can be designed. According to the wing-geometry provided by Alenia, the WT-model will be actuated with four kinematic stations, one station per wing-rib (located in the same plane), as can be seen in Figure 1 marked as WTT: 1760mm. The other dimensions in Figure 1 stand for the ground-test (GT) section and a Bird-Strike-test (BST) section. The ground-test will be used to perform a life-cycle test of the complete system (including wing-bending).
As stated above the kinematic system of the WT-segment is based on the deformation described at four different locations in span-wise direction and at each location with two additional load introduction points. With the movement-information (trajectories) on each of these eight points a non-structural model of the kinematic can be design and optimized.

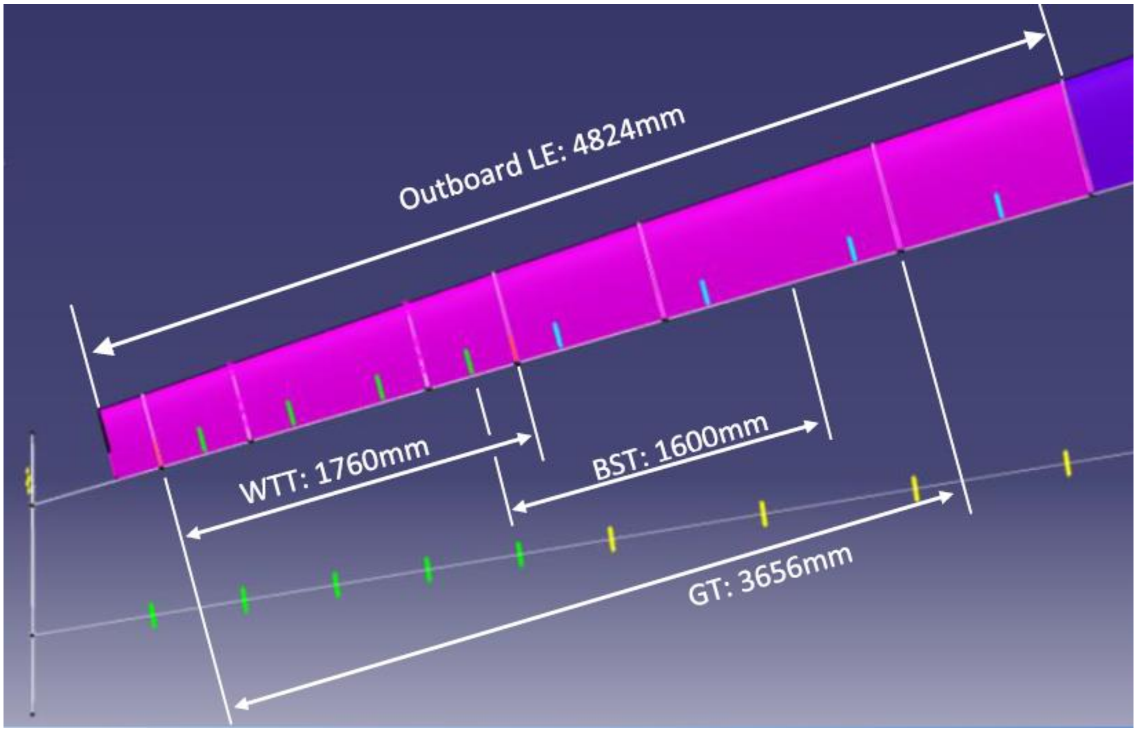



**Figure 1:** WT-, GT- and BST-Test Sections in AS01

### 2.1 Geometrical kinematic design

In this section the design of the non-structural kinematic system based on a set of requirements and optimization parameters is described. Each station can be regarded as a singular use-case and optimized as such, see Figure 2, but considering that the four stations have to be deployed simultaneously and evenly over the span a combined solution has to be found. Based on the above mentioned overall systems-requirement of low complexity and weight, the number of actuators, gearboxes and so forth had to be kept at a minimum. With this in mind it becomes obvious that a kinematic station design with individual actuators/motors is not favorable. An additional complication in this project is the extremely limited design space in the area of the outer wing, where the WT-test section is located. To design a highly moveable kinematic in such a tight space creates additional boundary conditions which had not been present or did not have to be considered for the SADE project. These boundary conditions are:

- Levers are not allowed to cross each other
- During the optimization loop the length of the levers has to be above a certain value (with regard to manufacturability and integration of hinges, bushings, etc.)
- Angle between skin and levers between 70°-110° for load introduction and positioning under load

With the work assignment to create a "low complexity" actuation system for the EADN the optimization loop also had to include multiple parameters with which the stations could be linked, for example the same droop angle and the same rotational axis. Linking the stations together would usually require some kind of gearbox for each station. By ensuring the same rotational axis and the same angle gearboxes can

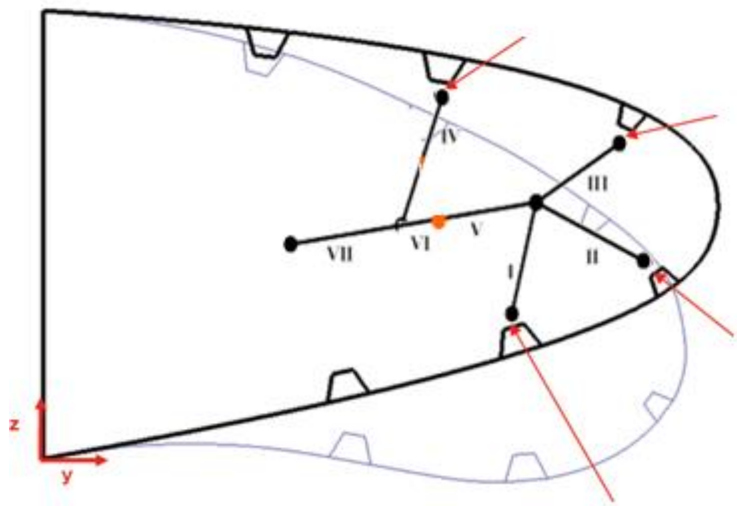
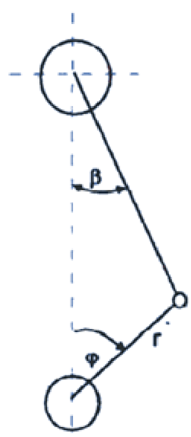



**Figure 2:** Cross-section of an enhanced adaptive droop nose with an integrated kinematic system for a morphing wing; red arrows indicate the load introduction points (exemplary demonstration).

be avoided. This also makes it possibly to have very similar kinematic stations and therefore similar or even identical parts.
Based on the trajectories for the kinematic stations (provided by DLR) a basic kinematic model for each station was developed and optimized with the above mentioned criteria in mind. For this design phase a tool was developed enabling quick analysis and optimization of the kinematics individually or as a group. Also this tool can be easily adapted to new geometries and optimization parameters.
By means of the equation of a push rod (Figure 3) it is obvious that a parameter study of rotational angle and the length of main lever or strut cannot be performed by simply solving the equation for rotational angle. The result would be four, partly complex, solutions. Therefor it is necessary that also the direction of rotation and the position of nodes need to be taken into consideration.




$$\boxed{x = r \cdot (1 - \cos\varphi) + l \cdot \left(1 - \sqrt{1 - \lambda^2 \cdot \sin^2\varphi}\right)}$$

x = Displacement
φ = Rotational angle
r = Length of main lever
l = Length of strut
λ = r/l = Ratio of struts

**Figure 3:** Simplification of the kinematic station by using the equation of a push rod in a co-moving reference frame.

In Figure 4 the four trajectories for the WT-stations along with a geometrical kinematic design can be seen. The kinematic is shown at 0° droop. As can be seen, the main hinge of each station is in the same

location in the z, y plane for each station. This position is one of the design/optimization variables. The position of this point has a big influence on the overall behavior of the kinematic chain. It does not only influence the droop performance but has also an influence on the loads on the structure and therefore directly influences the structural design and with this the weight of the system.
As mentioned above, one optimization aim is the uniformity of motion, namely the same droop angle of all four WT-stations at the same time. Figure  shows the variance in droop of all four stations in relation to each other, optimized for a 17° droop angle. Depending on the specification the variance of motion can be

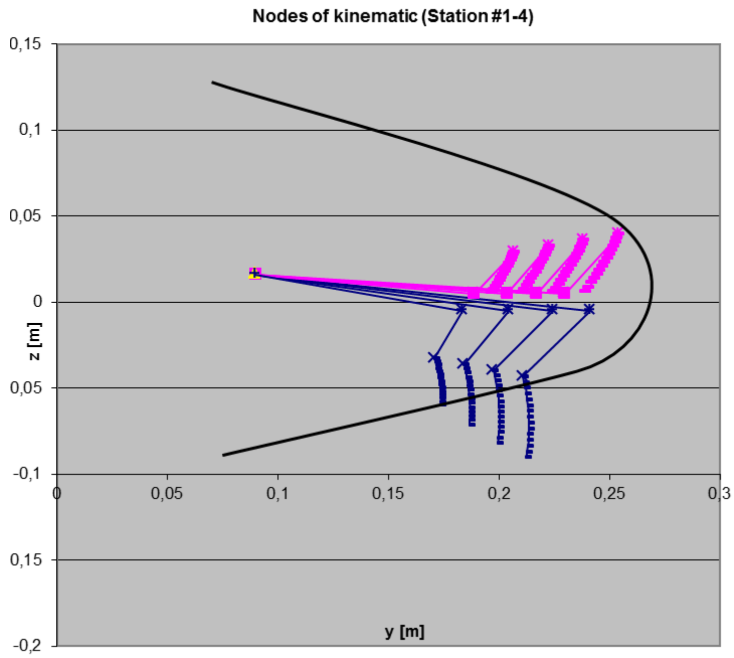



**Figure 4:** WT-Kinematic trajectories with hinge positions (airfoil just for visualization, NOT real geometry)

minimized either for the whole trajectory (V1), for a certain range of droop angles (V2) or for a specific target angle (V3). The depicted variance represents the squared differences of theoretical required droop angle to meet the trajectories (not the variation from the trajectories). The independent variables for the optimization are the position of hinge points which are adapted within given boundaries. At this point it is important to note, that the droop angle of the kinematics is not the droop angle of the leading edge. That means, even a small droop angle of the kinematic main lever can mean a high droop angle of the leading edge.

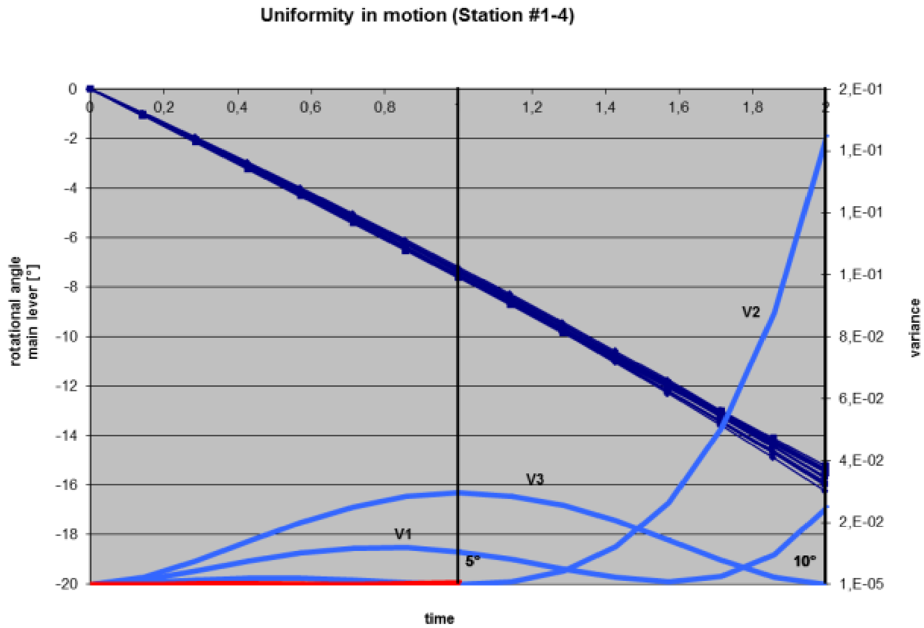



**Figure 5:** Uniformity of motion kinematic main lever

## 2.2 Detailed Kinematic Design

Based on the optimized design loop performed for the geometrical design, a full 3D model of the kinematic was designed with regard to the various load cases (provided by Alenia) and the mentioned boundary conditions (see above).

In the SADE project the kinematic solution was an individually actuated kinematic station. The actuator used was a rotary actuator. Adapting this design to the SARISTU geometry proved to be infeasible.

Figure 6 shows the result from the first design loop, based on the SADE concept. All four stations are connected via a torque shaft and driven by a singular rotary actuator. After a loads and precision assessment of this design was performed, it became clear that this was not feasible. The deformation of the torque-shaft grows with each following station, making the deformation less and less precise (the further away from the actuator). To reduce this deformation to an acceptable level would have meant a large increase in weight and in size of the torque shaft. This design was also too heavy, as the actuator alone weights roughly 30kg and is barely able to deliver sufficient torque for all load cases.

Besides the large difference in design space, the design loads in the SARISTU project are a lot higher than in SADE. This is in part due to the smaller size of the nose, as the shape of the nose acts as an automatic stiffener; additionally this (decrease in size) also reduces the torque lever of the load introduction points. The other reason for the load increase is, that the SADE project only worked with wind-tunnel loads, whereas SARISTU works with aircraft sizing load cases. The higher loads coupled with the smaller available space, made it impossible to simply scale the SADE system; therefore a

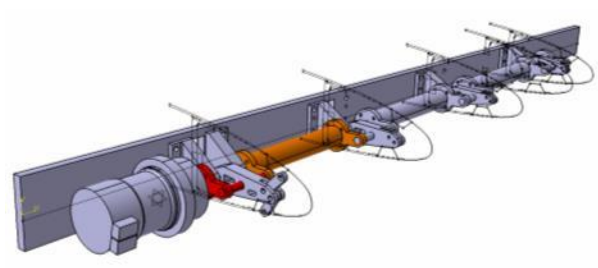


**Figure 6:** First design loop with rotary actuation and torque shaft

different solution had to be found. As a rotary system was not able to meet the requirements a linear kinematic system was the next logical step. For this the forward part of the design was kept as it was, the major change occurred for the drive-chain (force-transmission).

In this new kinematic drive-chain the linear motion of the actuator is translated via two hinges and one lever into a rotary motion. Figure 7 and Figure 8 show the finalized design in detail. The drive chain is a segmented round bar. Each segment is connected to the next via a spherical bearing to counter wing bending and tolerance issues. The drive chain is round for easier friction bearing design and easier assembly. The main lever is connected to the drive chain via the cross link. The cross-link has a spherical bearing on each end to allow for an out of plane rotational movement. The main lever is connected to the skin with two KAP levers. The KAP levers are mounted inside the skin brackets. The skin brackets are positioned inside the stringers of the skin. This was done with regard to the limited design space. By moving the force introduction points into the "skin – structure" design –space was created that was previously unusable. This enabled a better kinematic design but made the manufacturing more challenging. The brackets are integrated into the stringers during the manufacturing of the skin at INVENT GmbH.

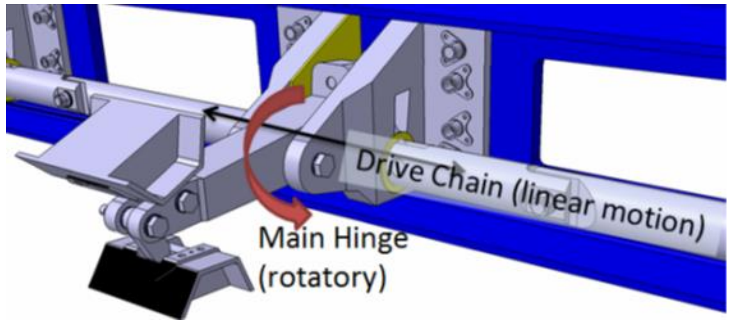



**Figure 7:** Linear kinematic concept; Functionality (1)

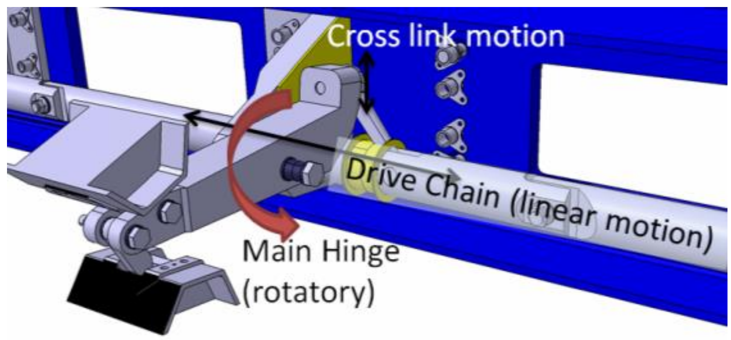



**Figure 8:** Linear kinematic concept; Functionality (2)

One huge benefit of this design is that the actuator forces are considerably reduced and at maximum deployment angle vanish completely. This is the result of the cross link position and angle to the drive chain. At a 90° angle between cross link and drive chain, the forces acting along the drive-chain are zero. Therefore the actuator only draws power during movement of the skin, thereby reducing the power requirements for the system dramatically. In undeployed position a mechanical break keeps the kinematic in place. As can be seen in Figure 9, the force to start the motion is relatively high, quickly reaches its maximum and declines than until at maximum deployment angle the force acting along the drive chain (and the actuator) is zero.

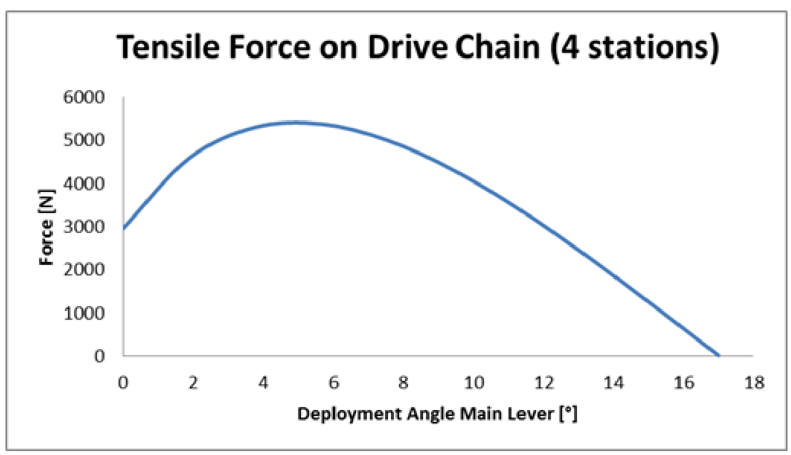



**Figure 9:** Force on Drive Chain dependent of deployment angle

The design is modular, making it easy to add or remove stations. Additionally the segment rearwards of the main hinge are identical on all stations.

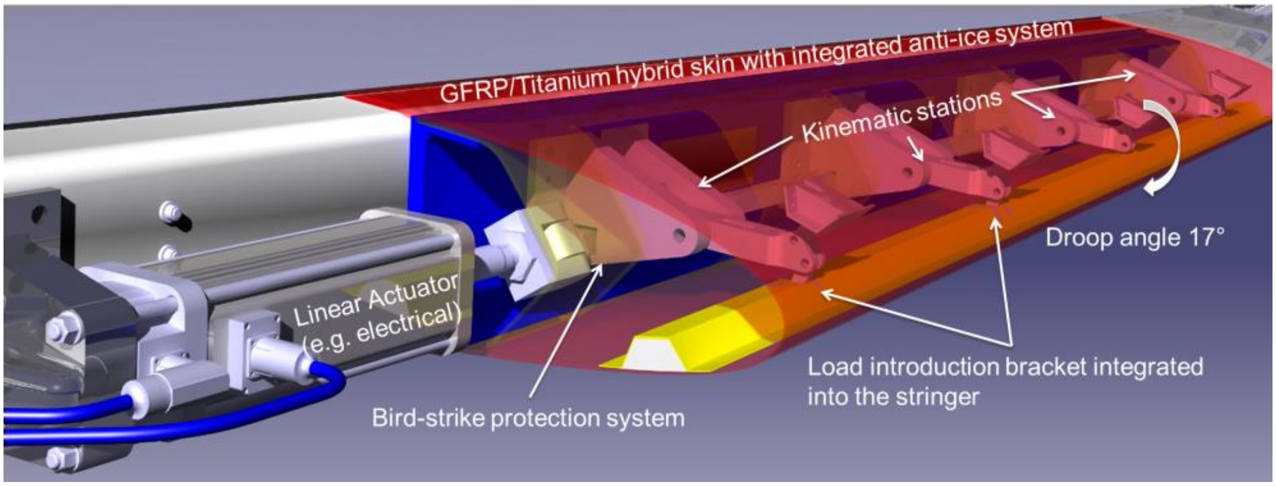



**Figure 10:** Full DMU of the AS01 WT-Droop Nose (several details/parts are hidden)

Figure 10 shows a DMU of the complete EADN with all relevant systems included.

### 2.2.1 Weight estimation and comparison

For the enhanced adaptive droop nose an integrated kinematic system was developed based on the aerodynamic requirements and the thereof derived load-cases. Based on these load-cases all parts were sized (non-standard parts) and/or selected (standard parts). All non-standard parts of the kinematic system were either analyzed using analytical methods (e.g. HSB) or a finite element model was created. With the sizing complete a weight assessment could be performed.

To be able to compare the two separately developed concepts (SADE vs. SARISTU) with each other in weight, at least a similarity in size had to be created. It was stated repeatedly that the SARISTU concept operates inside a much smaller space, therefore the system (shown above) is a lot smaller than the SADE concept. To equalize this difference the weight of each station in the SARISTU concept was measured and then used to extrapolate the larger stations. As the underlying airfoil is different, the most reliable factor for comparison is the chord-wise "length" of each station. This length is measured from the tip of the main

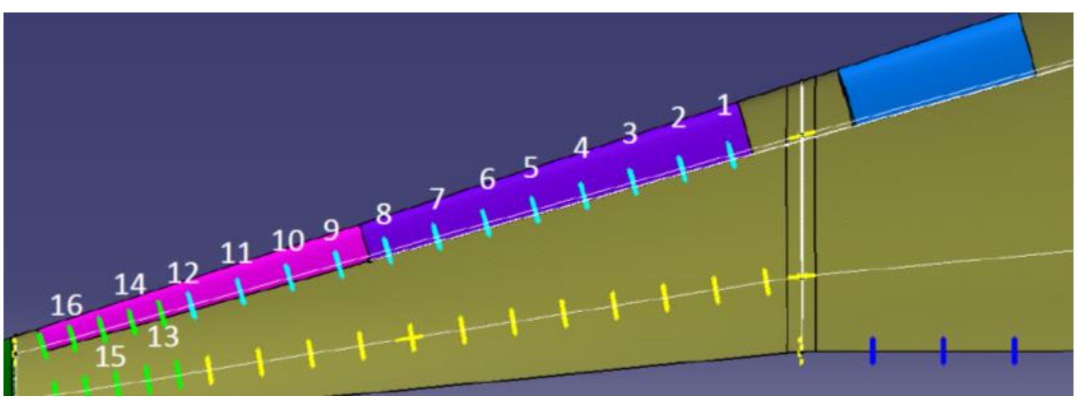



**Figure 11**: Kinematic stations on the wing (outboard of the kink)

lever to front of the front-spar. The weight of each station can be seen in Table 1 below, the weight herein contains only the structural mass of each station, the weight of the skin or the actuator is not considered. Figure 11 shows the position of the different stations along the front of the wing (outboard of the kink).

**Table 1:** Weight comparison of the different stations

| Position | RIB1 | RIB2 | **RIB3** | RIB4 | RIB5 | RIB6 | RIB7 | RIB8 | RIB9 |
|---|---|---|---|---|---|---|---|---|---|
| Weight [kg] | 4,000 | 3,816 | **3,629** | 3,442 | 3,255 | 3,068 | 2,881 | 2,694 | 2,507 |
| Lenght [m] | 0,635 | 0,577 | **0,525** | 0,477 | 0,434 | 0,394 | 0,358 | 0,326 | 0,296 |
| | Estimated Values | | | | | | | | |

| Position | RIB10 | RIB11 | RIB12 | RIB13 | RIB14 | RIB15 | RIB16 |
|---|---|---|---|---|---|---|---|
| Weight [kg] | 2,320 | 2,147 | 2,053 | 1,963 | 1,847 | 1,716 | 1,620 |
| Lenght [m] | 0,267 | 0,239 | 0,217 | 0,205 | 0,192 | 0,177 | 0,163 |

In Table 1 **RIB3** is high-lighted as this station is comparable in size to the in SADE developed station. Based on this a weight estimation of a complete station was performed.

Weight estimation of SARISTU Kinematic Station at RIB3:

≈ 3,6 kg (structure) + 1/8 of 24kg (motor) + 2,5kg (drivechain)

**= 9,1kg** (sized for “real” loads)

The motor assumed in this calculation is a 24kg electrical motor with a maximum continuous force of 31kN. It was further assumed that this motor would be used to drive stations on RIB1-8.
A drawing of the SADE kinematic can be seen in Figure 12. Fasteners are not shown, but included in the weight estimate.

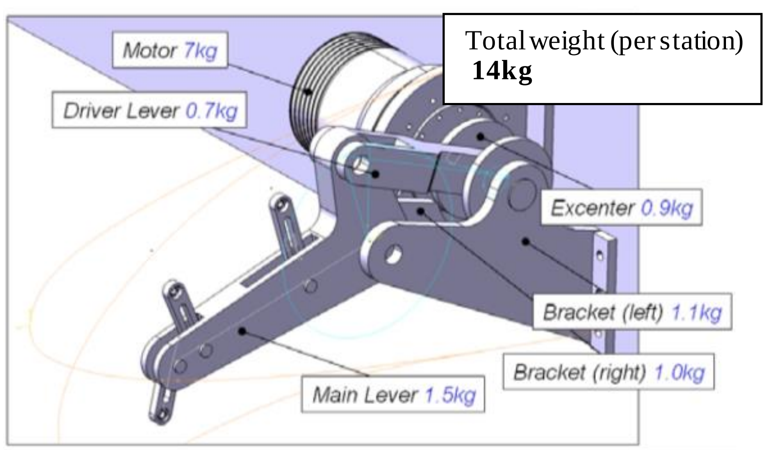



**Figure 12:** SADE Kinematic Station weight estimate

Figure 13 shows a SADE kinematic station at full deployment during initial functionality testing.

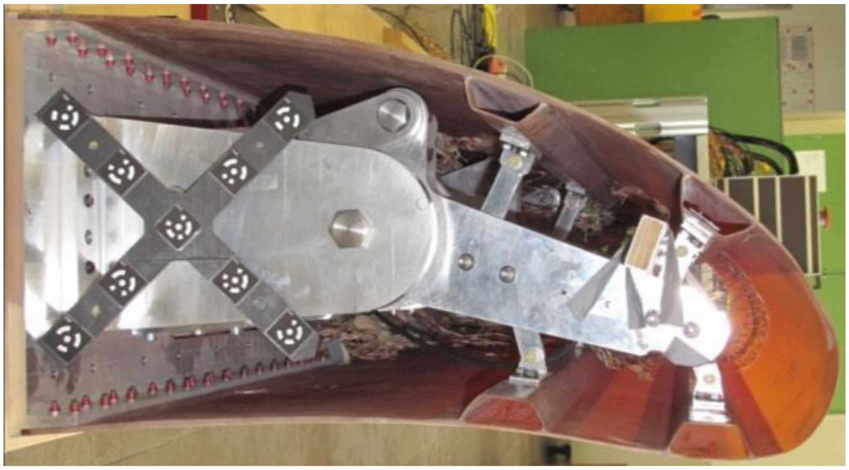


**Figure 13:** SADE Kinematic Station in WT Demonstrator (deployed position)

As shown in Figure 12 a SADE kinematic station weights about 7kg w/o the motor and 14kg with the motor.

The SARISTU kinematics achieves a weight reduction of about 35% in comparison to the SADE kinematics. Additionally it has to be mentioned, that the SADE kinematic was only designed for wind-tunnel loads, whereas the SARISTU kinematics was designed with regard to sizing loads of a wing (gust and maneuver loads).
Both designs are still not fully optimized, for example in both cases the selected motors are faster than required for the chosen tasks. Also a system assessment with regard to failure and hazard analyses should be performed, before a finalized weight assessment can be made. Nonetheless the SARISTU design shows an improvement over the SADE concept in terms of weigh and scalability.

## 3. Conclusion

Over the course of the paper the challenges related to the development of a highly integrated adaptive droop nose kinematic was explained. The various design requirements as well as an optimization concept was presented. The design tool enables to optimize the kinematics to respect the specified trajectories by taking into consideration the length of levers and the angle between skin and lever. Likewise an emphasis can be placed on a selected range of the trajectories to increase the level of accuracy there. In order to simplify the actuation system the kinematics can be designed for identical droop angle and rotational axis for all kinematic stations.
Based on the optimal solution a detailed mechanical design was performed and compared to a previous development. It was noted, that the design still is not completely optimized in terms of weight and that for an assessment on aircraft level a safety hazard analysis should be performed. However the comparison showed that significant progress in terms of weigh reduction was made. Also the scalability of the concepts was demonstrated. The complexity in terms of number of parts was reduced as much as possible. As a first final assembly of the complete system has not been completed as of this date it was not possible to perform a final assessment of the system complexity.

## ACKNOWLEDGMENTS

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