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Electromechanical Thrust Vector Control Systems for the Vega-C launcher

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Abstract

SABCA has designed electrical Thrust Vector Control (TVC) systems for the new VEGA-C launcher stages, based on the experience and lessons learned of the VEGA TVCs in operation since the first VEGA flight in February 2012. The paper presents the main drivers and lessons learned introduced in the design of this new generation of TVC systems.

1. Introduction

The VEGA-C launcher, currently under development, is the evolution of the VEGA European launcher. It has been introduced to

- Increase performances, with a 2200 kg load capacity in LEO (a 700 kg increase with regard to VEGA)
- Reduce operating costs
- Reduce dependency on non-European sources

Like VEGA, VEGA-C consists of 3 stages based on solid propulsion engines and a 4th stage based on a liquid propulsion engine.

The first stage is based on the new P120C solid rocket motor, which is the largest monolithic carbon fibre SRM ever built. The P120C motor is also used as booster for the new Ariane 6 launcher, serving as a common building block for both launchers.

The second stage with the new Zefiro-40 (Z40) motor will contain about 36 tons of solid propellant providing an average thrust of 1100 kN.

The Zefiro-9, reused from VEGA, serves as third stage. No modification has been brought to the TVC system.

The AVUM+ upper stage is derived from the current VEGA AVUM with a lighter structure. However the TVC system remains the same.

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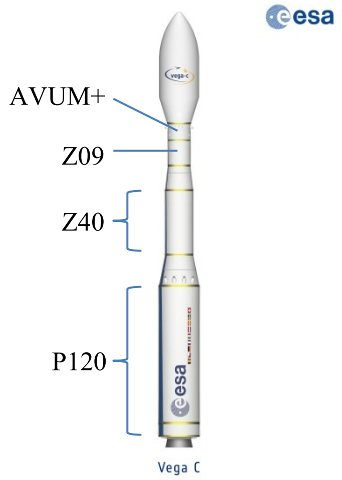

Figure 1: Vega-C launcher view

The architecture and specificities of the two new TVCs for the VEGA-C launcher, the P120 and Z40 ones, are detailed hereafter.

2. TVC general architecture

2.1. Supported functions

The main function of the TVC is to steer the stage's nozzle, in order to control the direction of the thrust vector, and thereby control the trajectory of the launcher. This function is physically ensured by a pair of electromechanical actuators (EMA) set at 90° from each other, which are connected to both the nozzle and the launcher structure. The controlled elongation of the EMAs allows to deflect the nozzle with regard to launcher structure.

In order to correctly fulfil its main function, the TVC supports a number of secondary functions:

- To communicate with the launcher's On-Board Computer (OBC)
- To damp nozzle swivelling oscillations to avoid transmitting high loads to the structure
- To generate the high power needed to actuate the nozzle
- To sustain the harsh thermo-mechanical environment within the stage
- To ensure high reliability by providing
  - health monitoring telemetry
  - fault tolerancy wherever possible within the system

2.2. TVC components

The TVC consists of the following equipments:

- Two electromechanical actuators (EMA) which piston elongation is driven by an electrical motor through a rollerscrew,
- An Integrated Power and Drive Unit (IPDU) driving and controlling the EMA's motors according to the elongation order received from the OBC,
- A High Power Supply (HPS), made of one or several interconnected battery modules, delivering power needed for actuation to the IPDU,
- A cable harness ensuring the interconnection of the preceding equipments, allowing power and data flow between them.

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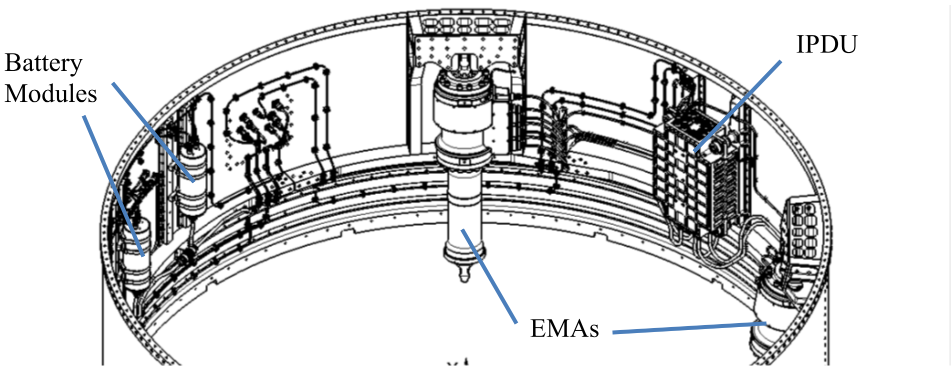

Figure 2: TVC layout within P120 interstage

2.3. External interfaces

The TVC exhibits the following external electrical interfaces:

- 1553 bus for communication with the OBC
- Low power supply interface to connect to the +55V on-board network
- Maintenance interface for software upload
- HPS interface to receive the battery ignition signal

IPDU and HPS battery modules feature bolted mechanical interfaces to be mounted on the launcher inner structure. The EMAs are equipped with a spherical bearing at each extremity to connect to the nozzle (EMA piston side) and the launcher structure (EMA rear side), with axles.

3. Commonality usage

In order to reduce development and operational costs, common or similar elements are shared between the P120 and Z40 TVCs:

- P120 and Z40 EMAs share the same architecture, the Z40 EMA being a reduced scale version of the P120 EMA, and the same subcomponents are used whenever possible, e.g. the same angular position sensor is used in both EMAs
- The IPDU is the same for both TVCs
- P120 and Z40 HPS are using the same battery modules. Only the quantity of modules differs, with a single battery module on Z40 and two battery modules connected in serie on P120

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4. VEGA-C TVC equipments detailed description
4.1. EMA

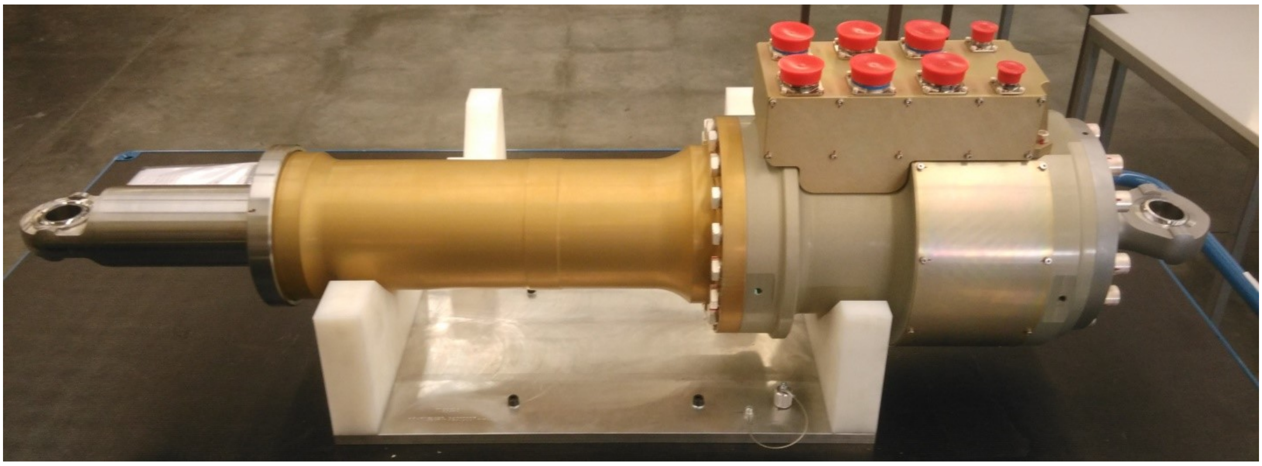

Figure 3: P120 EMA

The EMA consists of a brushless permanent magnet synchronous motor that drives a rollerscrew which transforms the rotational motion into a linear motion.
In order to allow the control of the EMA elongation by the IPDU, the EMA is equipped with the following sensors:

- A linear position sensor, specifically a LVDT placed at EMA centre, within the hollow shaft of the rollerscrew
- An angular position sensor, measuring the angular position of the electrical motor
- A load sensor at the rear end of the EMA, which measure is used into the damping algorithm which goal is to damp the nozzle swivelling oscillations (see §2.1)

With regard to the previous generation EMAs used on the current VEGA launcher, several innovations have been introduced in the design of the VEGA-C EMAs.

VEGA-C EMAs use a direct-drive architecture, with the electrical motor being centered around the EMA longitudinal axis and driving directly the rollerscrew without the use of a gearbox. The removal of the gearbox used in the previous "deported motor" architecture leads to a reduction of the number of EMA elements, a simplification of the assembly operations and ultimately a cost decrease.
Moreover, the concentric design implied by the direct-drive architecture suppress the unbalance present in a "deported motor" design

The electrical motor has been designed to be fault-tolerant to the loss of one phase, i.e. to continue to operate on N-1 phases even if with degraded performance, by

- Segregating each phase winding in separate slots to avoid fault propagation
- Oversizing the motor to allow a compensation current to flow through the remaining phase in order to compensate for the lost phase

The rollerscrew is no more supported by classical bearings, but by an innovative "zero-lead nut" developed by SABCA and SKF. The zero-lead nut is based on the principle of the translating rollerscrew nut, but with the addition of kinematic constraint which cancel the axial travel of the nut with regard to the screw. Like the classical bearing it replaces, the zero-lead nut sustain the axial load coming through the screw.
The zero-lead nut advantages over a classical bearing are a higher compactness and a reduced rotating inertia.

The EMAs elongation is no more measured by the linear position sensor, but derived through calculation from the angular displacement measured by the angular position sensor, knowing the fixed relation between the angular displacement of the electrical motor and the linear displacement of the EMA's piston.
The linear position sensor is now only used at TVC initialisation to get an absolute initial linear position, and is not used afterward.
Using the angular position sensor improves the overall accuracy of the linear position measure, as it is constant over the whole actuator stroke, where a classical LVDT accuracy decreased when it moves away from the central position.

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The following table summarizes the main characteristics and performances of both P120 and Z40 EMAs

Table 1: EMAs main characteristics and performances

	P120	**Z40**
Mass [kg]	120	60
Pin-to-pin length at neutral position [mm]	1314	987.7
Operational stroke [mm]	-167/+195	-120/+120
Maximum linear speed [mm/s]	380	380
Stall load [kN]	135	55
Output power [kW]	30	10
Positioning bandwidth at -3dB [Hz]	8	7

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4.2. IPDU

The IPDU consists of

- An Electronic Control Unit (ECU), in charge of communication with the OBC, TVC sensors conditioning, and execution of the TVC control algorithm
- A Power Module (PM), made up of 2 Electronic Power Units (EPU), one per EMA, and a power input stage
  - An EPU drives the EMA's motor through a full bridge (H-bridge) inverter which modulates DC voltage coming from the High Power Supply into AC voltage based on the Pulse Width Modulation (PWM) principle
  - The power input stage, located at the interface with the HPS, features a filter ensuring the stability of the DC bus as well as current and voltage sensors for monitoring of the IPDU input voltage and current

Based on lessons learnt from the VEGA TVCs, a modular IPDU architecture has been adopted on VEGA-C: the EPUs components (mainly inverter's IGBTs, power capacitors and driver board) are mounted on power blocks, one power block per phase, which are then assembled into the IPDU. This allows to execute more mounting operations on a standard subassembly (the power block) and to simplify the final assembly of the IPDU, thereby decreasing the assembly costs of the IPDU.

The ECU runs the TVC control algorithm on a CLP processor. CLP means Control Loop Processor and has been developed by SABCA in the frame of ESA's General Support Technology Program (GSTP).
The CLP is a deterministic processor for hard real-time applications, targeting electrical actuation subsystems, which main characteristics are

- Dual core architecture with on-chip intercommunication memory
- Cache-free and un-interruptible architecture
- IEEE-754 single precision
- RTBT (Real-time background tracer) for non-intrusive real-time software debugging
- On-chip communication bus controller:
  - Dual Space Wire
  - MIL-STD-1553RT
  - CAN with transceiver redundancy management
- Integrated SEU detection and correction mechanism
- 24 programmable PWM timers

VEGA-C IPDU is equipped with a tailored version of the generic CLP, running on a FPGA.

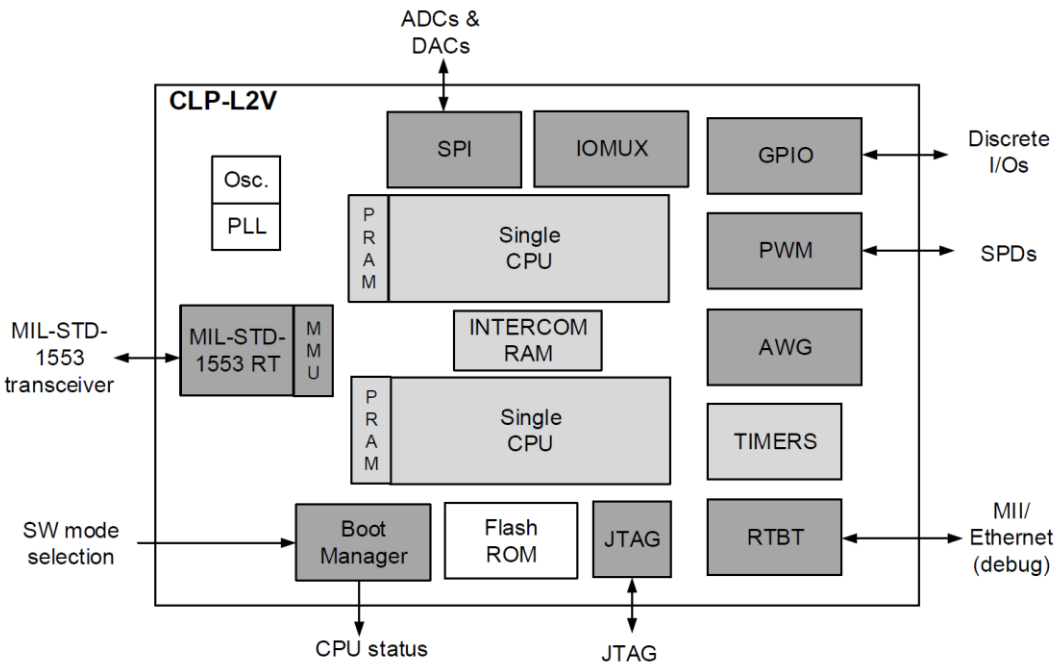

Figure 4: Vega-C specific CLP processor architecture

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Taking into account return of experience from VEGA, the EEE components policy applied to VEGA-C TVC has been opened to allow the use of other components than Hi-Rel components, such as automotive or MIL-plastic ones. The use of such components allows to

- Reduce costs
- Benefit from a wider range of values, volume, functions and packages for those components
- Benefit from the return of experience on components produced at high volume and also submitted to severe and harsh environments, such as ones encountered in aeronautics or automotive

Other noticeable evolutions with regard to previous VEGA IPDU are

- The replacement of current transducers by shunt sensors, thereby reducing cost and complexity
- The removal of a power switch at the high power input of the IPDU, thanks to the use of thermal batteries for the High Power Supply, which cannot deliver current at inert state and are presented in the next chapter

The following table summarizes the main characteristics and performances of the Vega-C IPDU.

Table 2: IPDU main characteristics and performances

Mass [kg]	51
Outer dimensions [mm]	560 x 383 x 205
Low power supply voltage [V]	55
Communication protocol	1553 bus
Output power per lane [kW]	55

4.3. High Power Supply

Both P120 and Z40 HPS are based on the same thermal battery modules, developed by ASB company. Z40 HPS consists of a single such battery module, while the P120 HPS consists of two battery modules interconnected in series.

The use of thermal batteries is an important evolution from the previous TVC design, which was using Lithium-Ion batteries.
Thermal batteries electrolyte is solid in ambient conditions and therefore the battery is inert (i.e. does not deliver current) until the battery is activated through the ignition of heat pellets placed inside the battery. The electrolyte then melts, allowing current to flow from the battery. Due to its concept, the thermal battery module is a single usage equipment, as it returns to its inert state once the module temperature cool down back to the temperature where electrolyte solidifies again.

The main advantage brought by the use of thermal batteries is a simplification of the related operational procedures:

- There is no self-discharge, thermal batteries do not need to be recharged during storage period
- No transportation limitation, as battery is inert prior to activation
- No need to have a power switch on the IPDU and specific procedures to ensure safety against electrical shocks, as battery is inert prior to activation

The active part of the battery is composed of stacked cells connected in series, each cell being consisting of anode, electrolyte and cathode layers.
At each end of the active stack, there are collectors whose leads are connected to the power connector of the battery. Fuse strips (which are pyrotechnic composition in paper form) are placed along the side of the active stack, in direct contact with the cell edge, which ignite the heat pellets placed between the cells.

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The activation of the battery is ensured by two electrical igniters, which ignite the fuse strips.

The following table summarizes the main characteristics and performances of the Vega-C battery module.

Table 3: Thermal battery module main characteristics

Mass [kg]	12.3
Outer dimensions [mm]	368 x 150 x 150
No-load voltage [V]	185
Peak output power [kW]	37

4.4. Software and control algorithm

A new control feature has been introduced in the VEGA-C TVC software, which is the power sharing algorithm.

The power sharing algorithm dynamically allocates the available power from the HPS to the 2 EMAs, proportionality to the power demand from each EMA. This has no impact on the overall performance of the TVC because the power needed to actuate the nozzle is the same whatever the direction of the movement, meaning that the same global amount of power can be shared between the EMAs. Only the repartition of the power between the EMAs changes according to the direction of the actuation.

The power sharing algorithm therefore allows to optimize the sizing of the High Power Supply with regard to previous TVC, where the power was not shared among the EMAs and the HPS was sized to deliver 2 times the maximum power needed by a single EMA. This means the use of power sharing algorithm has allowed a reduction by nearly a factor 2 of the HPS size in terms of power, leading to a decrease of cost and mass.

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5. Program status

P120 and Z40 TVC have been both successfully tested twice during static firing tests (SFT) at stage level.

Table 4: Vega-C P120 and Z40 static firing test list

Event	Date	Location	Outcome
Z40 development model SFT	07/03/2018	Sardinia	Success
P120 development model SFT	16/07/2018	Kourou	Success
P120 qualification model SFT	28/01/2019	Kourou	Success
Z40 qualification model SFT	07/05/2019	Sardinia	Success

Figure 5: Aerial view of the Z40 development model static firing test in Sardinia, Italy

The TVC is undergoing its qualification campaign in the next months, the VEGA-C maiden flight being scheduled during the first quarter of 2020.

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