Challenges in Power Management and Distribution for Robotic Systems in Space

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Abstract—**Modern space missions show an increasing demand for remote controllable robotic systems to perform assembly, service or manipulation tasks. All these robotic missions require a tailored and reliable power management and distribution solution. It has to ensure that the performance of the overall system is fulfilled with highest possible efficiency. Power supply and distribution solutions are discussed within this paper for the newly developed the Compliant Assistance and Exploration SpAce Robot (CAESAR) built by the DLR Robotics and Mechatronics Center. These solutions are based on the analysis of power supply systems used in heritage systems such as space robotic experiments, as well as medical and industrial robots. System requirements and applicable space mission requirements are taken into account in the decision process. The selection of the appropriate power supply and distribution system is a key decision regarding the reliable operation of the overall system. This decision also defines the required interface between the robotic arm and the satellite.**

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1. INTRODUCTION

Robotic systems are a required element for future space missions as they are able to perform multiple tasks by remote control. Since 2005 the Institute of Robotics and Mechatronics of the German Aerospace Center (DLR-RM) conducts research in the field of robotic systems in space. Successfully completed robotic space missions include the RObotic Components Verification on the ISS (ROKVISS) (2005 to 2010) [1], Kontur-2 (2011 to 2016) [2], and the Mobile Asteroid Surface Scout (MASCOT) deep space mission (2014 to 2018) [3]. In 2024 the Martian Moon eXploration (MMX) Rover mission will be launched as part of the JAXA MMX mission. The rover is equipped with eight robotic drives to upright itself autonomously after landing and to drive on the Martian moon Phobos. It is developed by DLR and Centre National d'Études Spatiales (CNES) [4]. A reliable power supply is a prerequisite for the success of the mission. The CAESAR arm built by DLR-RM [5] is introduced in Section 2. It covers the desired specifications and gives an overview over the technology used in CAESAR.

Components of a modular robotic joint and their requirements are discussed in Section 3. One of the major design targets is to reduce its mechanical space and weight, as well as to increase the power conversion efficiency. The harsh environment including radiation, vibration and temperature range places further limitations. Power supply concepts of ROKVISS, the Canadarm on the International Space Station (ISS) [6], and traditional space power conditioning and distribution topologies used for satellites [7] are discussed in Section 4. Concepts of power management used in the industry (e.g. the DLR-LWR (Light Weight Robot) robotic arm developed by DLR-RM [8]) or in the medical sector (e.g. the versatile robotic arm for medical applications (MIRO) by DLR-RM [9]) stand out due to their modularity, lightweight construction and reliability. Possible combinations are considered and discussed for their suitability of usage in the CEASAR arm. An overview of the power supply requirements of the different components used within a robotic arm is discussed in Section 5. Section 6 covers the design challenges and approaches on an optimized power distribution of modularized robotic joints within the CAESAR arm [5]. The conclusion summarize the results and the benefits of the proposed power management and distribution architectures based on the CAESAR project. Further capabilities on optimization and modularization for future missions are mentioned at the end of this paper.

2. THE CAESAR ARM

The Compliant Assistance and Exploration SpAce Robot (CAESAR) is the continuation in the development of force and torque controlled robot systems at the DLR-RM.

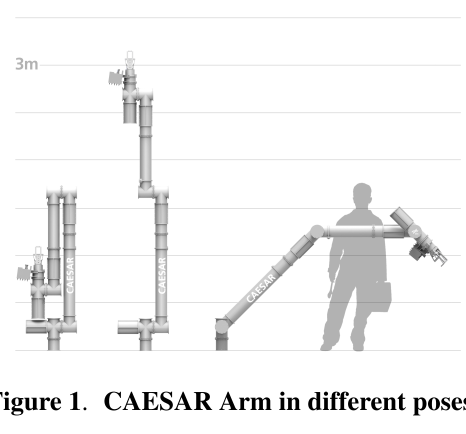

Figure 1. CAESAR Arm in different poses

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It is designed for a variety of on-orbit services e.g. assembly, maintenance, repair and debris removal in Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO). The CAESAR design requirements are driven by the use-cases in LEO, GEO, as well as deep space missions. Figure 1 shows various example of the CAESAR Arm in storage, full extension or operational configuration. The mass of the robotic arm is approximately 60 kg. Each joint can generate a torque of 80 Nm, a velocity up to 10° per second and a range of motion of 340°. It can operate in a temperature range between -20°C and +60°C and can be stored within -50°C and +60°C ambient temperature. The radiation hardness of 40 krads TID is based on a designed mission time of 10 years in GEO. Furthermore, a redundancy of the electronics is provided to increase the reliability of the robotic arm [5].

Electronic Block Overview

An overview of construction of one non-redundant Electronic Block (EB) together with the connection design of joint 1 and joint 2 is shown in Figure 2.

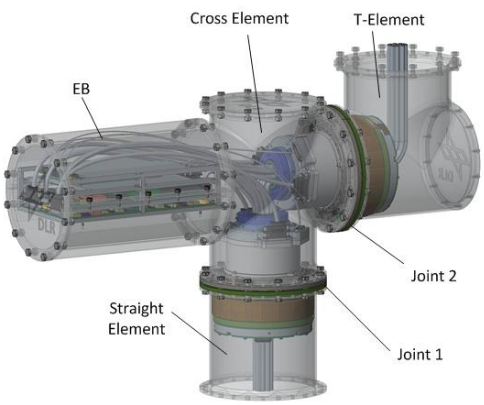

Figure 2. CAESAR Electronic Block (EB) with two joints and integrated harness model [5]

An EB consists of one Power Supply Unit (PSU), one Power Inverter (PI) and one Joint Control Unit (JCU). Two motors of each of the seven joints are controlled by one EB. The detailed function of these is described in the next section. As a result, an arm consists of four nominal and four redundant EBs. The communication between the EBs is handled by EtherCAT and is galvanically isolated by a signal transformer on both sides. The harness for communication between the EBs, the power supply and sensor interface of each EB, as well as the heater harness is routed through the hollow shaft of each joint. The uniform design of each EB in the arm ensures modularity and simplified development of the system.

3. Overview and Requirements of Robotic Joint Subsystems

Robotic joints such as those being developed at DLR consist of several submodules. These are required to enable a modular design of robotic arms and to ensure reusability. Figure 3 shows an overview over the required subsystems of a robotic joint. To move the shown joint mechanically a motor is needed.

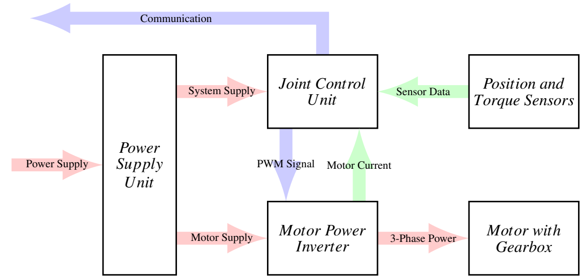

Figure 3. Required subsystems of a robotic joint

This motor is powered by a Motor Power Inverter (PI). Depending on the application and the required torque or angular speed, an additional gearbox is required. The Inverter amplifies the control signals of the Joint Control Unit (JCU) and sends the measured motor currents back.
The JCU calculates the control signals based on the motor currents as well as on torque and position values measured by the sensors placed on the motor or the gearbox. Communication with other robotic joints or computers is also performed by the JCU.
Every subsystem of a robotic joint is supplied with the required voltages and currents by the PSU. In addition, it protects the power supply lines of sensitive modules from overload in a Single Event Effect (SEE) caused by radiation.
The robot joints have to meet a number of requirements. These are extended and more intensively, particularly in harsh environments compared to industrial requirements. Figure 4 shows the most common requirements for robotic missions in space.

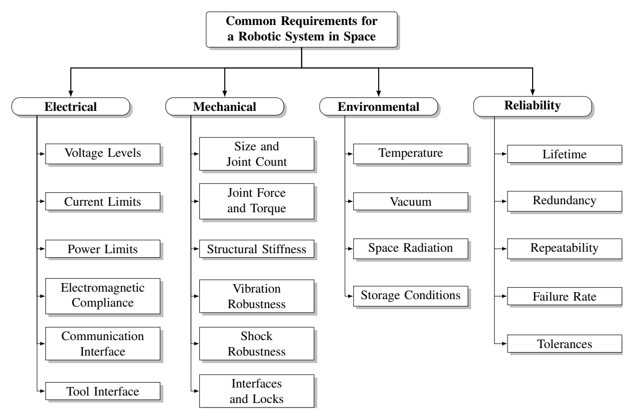

Figure 4. Overview on requirements for a robotic system

These requirements are mainly covered in terms of the electrical and mechanical systems, as well as the environmental and reliability considerations.

4. Power Supply and Distribution in Heritage Systems

DLR Light Weight Robot

The DLR Light Weight Robot (LWR) has an outstanding ratio of payload to total mass. Though it weights only 14 kg it is able to handle payloads of 14 kg over the whole dynamic range. Light-weight gears, powerful motors and weight optimized brakes have been integrated into the robot.

The robot has seven degrees of freedom which results in advanced flexibility in comparison to standard industrial robots. The electronics, including the power converters are integrated into the robot arm. No bulky external rack is needed. The integrated sensors are most progressive - each of the Light Weight Robot joints has a motor position sensor and a sensor for joint output position and joint torque. Thus the robot can be in operated position, compliance and torque control mode. The highly capable system of the LWR was transferred to KUKA in 2004.
The LWRs have two galvanically isolated power buses, 48 V for the electronic supply and 48 V for the PI and motor supply. The power converter has been developed for three phase motors. Two phase currents and the bridge voltage are measured galvanically isolated. Each joint has its own power supply unit. The galvanically isolated supply voltages are generated from the 48 V-DC-Input. The supply unit powers the controller board, the power inverter and all sensors. An overall of six internal voltages are generated.

ROKVISS

The German space robotic project ROKVISS was launched towards the ISS in 2004 and the joints returned to earth in 2011. The return of the joints allows detailed analysis and advanced tests of space robotic joints for the first time. ROKVISS aimed at the space qualification of DLR LWR modules (modified for a space environment) with a reduced setup of a two degree of freedom robot arm mounted on the exterior of the ISS, as shown in Figure 5.

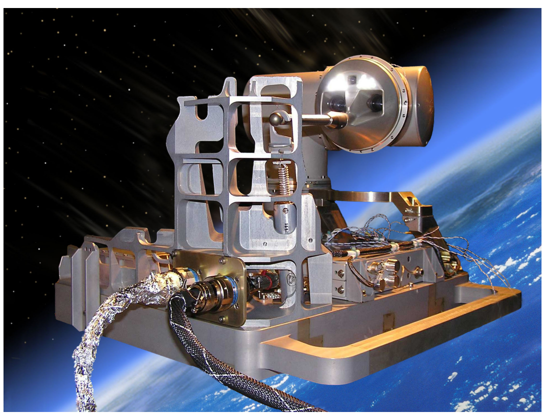

Figure 5. ROKVISS Experiment

With this experiment DLR could prove the concept with the use of some Components Off The Shelf (COTS) within a very tight and highly integrated mechatronic device with the modular joint concept. After more than five years of successful operation without any failure, the innovative mechanical and electronic concept is validated for the use in further space projects. ROKVISS was also a telerobotic demonstrator with real-time stereo-video transmission and tactile feedback [10]. The successful telepresence with force reflection to the operator on Earth was the second major achievement of ROKVISS besides the component verification.
The power design of the ROKVISS system is similar to the LWR design at the joint and motor level but in most cases the two 48 V input voltages for the LWR are generated with commercial laboratory supplies or batteries. For ROKVISS a space qualified, 28 V input voltage Power Distribution Unit (PDU) was designed (by Kayser-Threde, now OHB) to provide the necessary voltages. The ROKVISS PDU is composed of the following building blocks:

- EMC filter
- Voltage and current limiter
- Auxiliary converter and associated current limiter
- Control logic and its respectively decoupled interface with the On-Board-Computer (OBC)
- Supply branch for the video chain subsystem
- Two supply branches for the electronics of two joints (28 V)
- Two branches of motor supply of two joints, including galvanic DC/DC isolation (28 V)
- Sensing means for external temperature monitoring and input voltage feedback

DLR MIRO

The DLR MIRO is a versatile lightweight robot for surgical applications developed by the DLR-RM. The area of application of the robot is the extra corporeal guidance of instruments in open and minimally invasive surgery. Specialized surgeries can be performed by adding tailored instruments to the MIRO robot. Due to the use in the medical environment, safe operation is necessary in order not to expose the patient to any risk. The power supply within the robot is ensured via a separate motor and system supply. The mains power converter for these supplies is located outside of the robot in a separate unit next to the robot. A serial power supply connection from one joint module to the next is used to reduce the amount of wires through the hollow shaft [9] [11].

Canadarm

One current operating robotic arm in space on the International Space Station (ISS) is the Canadarm. It is used for assembly and science tasks as well as a workhorse for assisting astronauts performing space walks. This robotic arm was previously developed as a Shuttle Remote Manipulator System (SRMS) and had its inaugural flight in November 1981 [6]. Based on the above data, the Canadarm is an outstanding system that can serve as a model for the CAESAR power supply concept and implementation. Unfortunately, little information regarding the power supply and power distribution is published or accessible.

Satellite Power Condition and Distribution Unit (PCDU)

Regulated Bus Systems used in traditional Space Systems like geostationary satellites [7] [12] or the ISS [13] uses separate modules to condition and distribute the power to the individual loads as shown in Figure 6. Solar Array Regulation

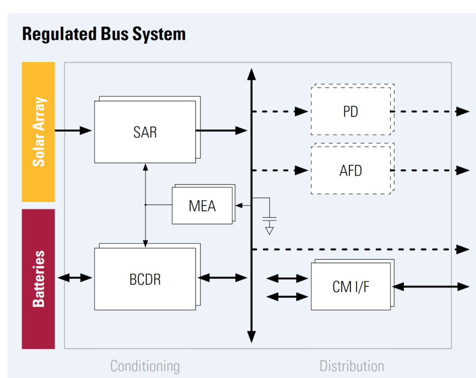

Figure 6. Common Satellites Space Power Bus Architecture [7]

(SAR) is used to condition the power supplied by the solar array to the power bus. A Battery Charge and Discharge Regulator (BCDR) controls power transfer between the battery and the power bus according to the control signals of the Main Error Amplifier (MEA). The loads are supplied by the power bus through Actuator Firing Devices (AFD) or Power Link Distributions (PD) combined with an optional Latching Current Limiter (LCL). For telemetry with the power system a Command and Monitoring Interface (CM I/F) is used. The power flow of the PCDU is restricted to source the load from the power bus. Hence recouperation of energy from loads to the battery is permitted and not possible by using this power supply architecture.

5. POWER SUPPLY REQUIREMENTS OF CAESAR

This section covers the design process of the power supply for one EB. The CAESAR RA (Robotic Arm) is used as a target design system in the following sections. The advantages of the known and previously presented power supply systems have been incorporated into this design process.

Power supply and grounding within an EB

As part of the modular concept each EB can be seen as a self-contained subsystem within an RA. Thus, for the communication and wiring within an RA only the interfaces between the EBs and/or the central connections are relevant. One of these interfaces is the power supply that is handled by the PSU of each EB. To ensure a reliable control of a robotic joint various requirements have to be fulfilled by the power supply. It needs to satisfy three different types of electronic circuitries, which have their own requirements and reference potentials:

- *Power circuitry* is used for powering the motors connected to the PI. Due to the hard switching behavior of the PI based on the commanded PWM signal from the JCU this power circuitry emits the highest amount of noise on the supply net. It has to be immune against ripple on the power line caused by other EBs. The power consumption is the highest compared to other circuitries. It is referenced to the PGND reference potential.
- *Digital circuitry* requires a fast transient regulation and a low supply net impedance due to the fast communication and computation tasks. Based on the motor control task profile the dynamic load on the power consumption varies. These circuits can emit high frequency distortions on the power supply network. It can have an increased susceptible behavior on common mode noise on communication lines by using a low voltage for this task. It is referenced to the DGND reference potential.
- *Analog circuitry* requires an filtered and noise reduced supply to enable an undistorted measurement of the measured analog signals, such as sensors or Analog-to-Digital Converters (ADCs). The power consumption is minor compared to the other circuitries. It is referenced to the AGND reference potential.

To combine the requirements of these three different circuitries into one reliable system a comprehensive grounding concept is mandatory. For the EB used in CAESAR the grounding concept is shown in Figure 7. The external power delivery to the EB is referenced to the RTN-MOT (power return motors) and RTN-SYS (power return system) potentials. They are connected to the input terminals of the PSU of each EB only. This concept together with the galvanic isolation of the EtherCat communication interface ensures the mitigation of ground loops within the RA.

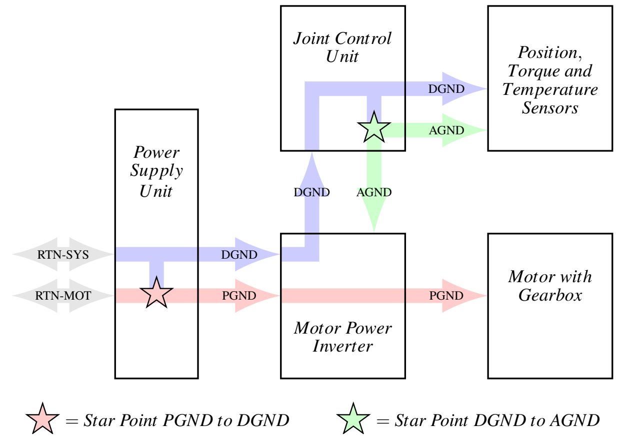

Figure 7. Grounding Structure of the CAESAR Electronic Block (EB)

The RTN-SYS is connected to the DGND reference potential and the RTN-MOT is connected to the PGND reference potential on the PSU. A starpoint connection between the PGND and DGND is also established as part of the PSU. The PGND and the DGND reference potential are handed over from the PSU to the PI by the connection between them. Therefore the highly disruptive motor currents of the power circuitry is separated from the digital and analog circuitries. The digital reference potential and the corresponding power supply lines required by the JCU is shared with the digital circuit of the PI. They are routed through the PI to the JCU. The analog supply is derived from the digital supply by an additional filter network to reduce the noise on the analog supply. Since the ADCs are located on the JCU and the sensors, the starpoint between DGND and AGND is placed next to the transition area between the digital and analog circuitries. The current measurement circuit on the PI as well as the sensors for position, torque and temperature connected to the JCU are referenced to the AGND potential and supplied by the filtered analog supply.
The PSU uses switching converters in a flyback topology to ensure no direct connection between the system supply and the internal circuitries of the subsystems by using a transformer. In the event of a failure of one converter switching component the loads are protected from the input voltage. This safety feature also improves reliability and robustness of the system.

Estimation on Power Consumption of one EB—Every device referenced to DGND or AGND is supplied by a conditioned power supply. The conditioning is handled by various power converters on the PSU that are referenced to RTN-SYS. The power demand of these devices are part of the System Power domain. The power conversion losses of the PSU to condition the supplies of the System Power domain are also part of it. The power demand of the power circuitry and the motor are part of the motor power.
Table 1 shows the individual and overall power requirements of the different subsystems in one EB according to their power domain and their reference potential. Every EB has a

EB Power Consumption			
EB Subsystem	Power Domain	Reference	Power Consumption
Motor Control Electronics	System	Digital (DGND)	≈ 4 W
Communication Electronics	System	Digital (DGND)	≈ 5 W
Sensor Suppy	System	Analog (AGND)	≈ 1 W
Power Supply Conversion	System	Power (RTN-SYS)	≈ 2 W
Motor Drive	Motor	Power (RTN-MOT)	up to 80 W per motor
Total EB System Power Consumption			12 W
Total EB Motor Power Consumption			up to 160 W

Table 1. Power Consumption overview of one EB

total system power consumption of 12 W and the motor power consumption can be up to 160 W. This value depends on the number of motors connected to the EB.

Power supply within a robotic arm

A power distribution design of an entire arm is based on the calculation on power requirements of a single EB. For the initial design of the system the proven ROKVISS system was used as a basis.

A system voltage of 28 V is chosen to achieve an acceptable compromise between robustness of the supply against transient disturbances and efficiency as well as increasing complexity of the PSU operating at higher input voltages. Furthermore, a supply voltage of 28 V provides compatibility with additional devices on the Tool Change Adapter port (TCA). Different voltage levels for the TCA based on the tool requirements are possible but will increase the complexity of the overall system. The voltage selection of the motor supply is built on knowledge gained from the DLR LWR and DLR MIRO robotic systems. According to the motor and PI design a voltage of 56 V is used for the Motor Power domain. This voltage is the result of a trade-off between cross-section reduction of the motor power harness and an efficient and space restricted power inverter design.

Estimation on Power Consumption of one RA—On the basis of the number of joints and EBs required, a total consumption of the RA can be estimated. A seven-joint RA requires four operational EBs. This calculation is shown in Table 2. 48 W are required for the system supply of all EBs. Additionally there is a TCA connected to the 28 V system power harness that can provide up to 200 W to the tool. Hence, the system power harness has to handle up to 248 W in total. The resulting current for this harness is 8.9 A.

The power consumption of the motors depends highly on the desired operating condition. In order to avoid possible limitations due to the power distribution, the total consumption is conservatively based on the assumption that all motors can be operated at their maximum power at the same time. This also provides some margin for future possible operating points that were not planned in advance. A total power of 560 W is therefore required with seven motors in operation. This equals a current of 10 A in the power harness for the motor power supply.

RA Power Consumption		
RA Subsystem	System Power	Motor Power
EB 1 to 3	≈ 12 W each	up to 160 W per EB
EB 4	≈ 12 W	up to 80 W
TCA	up to 200 W	-
RA Maximum Power Consumption	248 W	560 W
RA Maximum Current	8.9 A (with 28 V System Supply Voltage)	10 A (with 56 V Motor Supply Voltage)

Table 2. Power Consumption overview of one RA with seven joints

Base Power Isolation Unit Interface

The Base Power Isolation Unit (BPIU) is the central interface between the power connection of the satellite and the CAESAR arm. It enables the operation of the RA in combination with a satellite bus voltages from 28 V to 120 V. This unit has to handle and to condition the power flow from the satellite to the RA as well as to ensure a safe operation of the RA.

By using a galvanic isolation between every power input and output of the BPIU, it is possible to connect the CAESAR to heritage satellite bus systems. This isolation complies to the grounding requirements of those. The structure of the RA is connected to case ground that is isolated from the return connection on EB level. A grounding starpoint is required on system level of the RA to ensure no floating potentials within the RA. This requirement also ensures the compliance of the withstand voltage of each EB against case ground. Therefore the returns of the secondary side of the galvanic isolated power supply (RA side) are connected together and are also connected to the case ground at the BPIU to generate a low impedance single starpoint. Furthermore, the BPIU also acts as a filter to reduce the conducted emissions caused by the motors of the RA emitted to the spacecraft. Measurements show that the galvanic isolated topology used in the BPIU reduces the conducted emissions from the RA to the satellite power bus [14].

6. Power distribution solutions within CAESAR

From the previously defined current interfaces of the EB, a power supply of the system and the motors is required. These can be implemented individually or in combination. For the selection of the power distribution and supply topology, it has to be taken into account that torsion is present in to the cables caused by the rotating joints. The cables are therefore stressed mechanically. Excessively large cross-section of the entire cable bundle or of individual wires can lead to a fault caused by cable breakage, short-circuit or an incorrectly measured value of the joint torque. Various power distribution solutions within the RA are discussed in this section. The advantages and drawbacks of each individual solution and combination are shown. Based on the requirements of CAESAR and the trade-off between each solution the best fitted power distribution is selected.

Power Interface comparison for each Electronic Block

In this section different possibilities of the supply implementation of an EB are presented. For this purpose, the designs and their conditions and properties are discussed.

***M**otor and **S**ystem Supplies with **I**ndividual **R**eturns*

The Motor and System Supplies with Individual Returns (MSIR) requires four individual wires to the supply the system and motor electronics of one EB. A power connection example is shown in Figure 8.

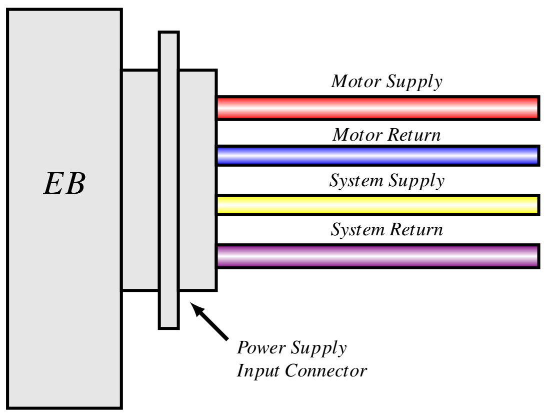

Figure 8. Power interface scheme for the MSIR variant

The power flow of the motor and power electronics are strictly separated from the power flow of the system. Consequently, this division ensures the highest immunity of the system against interference from the motor and the power electronics. In order for this concept to be functional, the system supply has to be individually galvanically isolated from the motor supply at each EB. This is required because the system supply reference has to be connected to the motor supply reference at each EB according to the discussed EB grounding scheme. The MSIR variant has already been deployed and tested on ROKVISS and DLR LWR systems.

***M**otor and **S**ystem Supplies with **C**ombined **R**eturn*

By combining the individual return lines of the motor and system of the MSIR, the Motor and System Supplies with Combined Return (MSCR) variant is analysed. This is characterized by separate supply lines of system and motor as well as a common return line as shown in Figure 9.

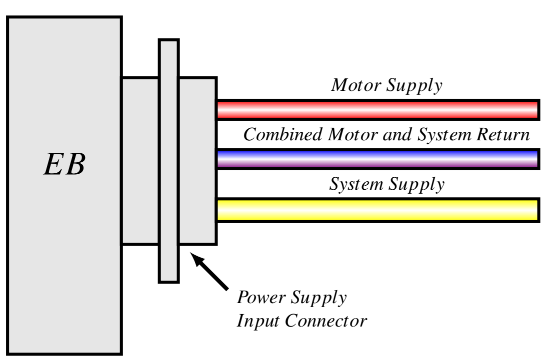

Figure 9. Power interface scheme for the MSCR variant

Three conductors are therefore required to supply one EB. Galvanic isolation of the system to motor supply is not required for this variant and simplifies the structure of the supply system, and thus reduces its complexity. The return currents of the motor and system supply add up on the common return line. This means that the conditioning and conversion of the system supply (PSU) has to be immune against the interference currents on the return line caused by motor operations. The MSCR power connection variant is used in the DLR MIRO robotic arm.

***C**ombined **M**otor and **S**ystem **S**upply*

The last supply option to be mentioned is the Combined Motor and System Supply (CMSS). In this case the system supply is completely combined with the motor supply. This means that only two supply lines are required as illustrated in Figure 10. Compared to MSIR and MSCR, the CMSS version

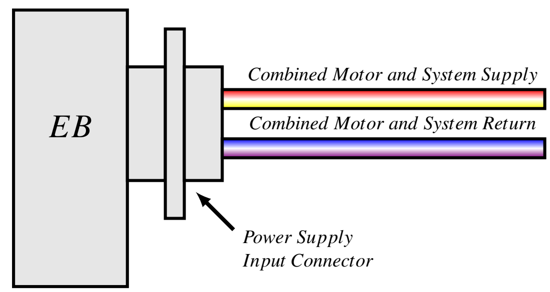

Figure 10. Power interface scheme for the CMSS variant

requires the smallest number of cables and connector power pins. This potentially saves space in the hollow shaft of the motors and reduces the connector size.

Power harness distribution within the robotic arm

Each previous discussed power interface to each EB results in a different power harness design. This power harness can either be distributed in a parallel way from the BPIU to each EB or in a daisy chain way from the BPIU or an EB to the next EB. Advantages and drawbacks of these distribution schemes in combination with the three different power interfaces of the EBs are discussed.

Parallel power distribution scheme—The parallel power distribution network is designed to have each EB connected directly to the BPIU by a power harness. An example of a parallel power distribution of a seven joint RA with four EBs and one TCA as in CAESAR is shown in figure 11. Five power harnesses are required from the BPIU to the individual loads in this use case. These have to be routed in parallel through the hollow shaft of the first joint. This joint also serves as the mounting point of the robotic arm to the satellite structure. This can lead to a bottleneck concerning the maximum hollow shaft occupancy of the first joint. Parallel power distribution is used in the power distribution networks of the conventional satellites to source and control individual loads by a PCDU [7]. The presented parallel power distribution scheme for the robotic arm is derived from it. The power harness can be distributed in parallel either in the MSIR, the MSCR or the CMSS version. The properties are part of the comparison in Table 3.

Serial power distribution scheme—With serial power distribution each EB takes the required power from one shared power harness. This is enabled by supplying EB 1 with power from the BPIU and then passing these lines on to EB 2 and so on. An example of the serial power distribution within a seven-

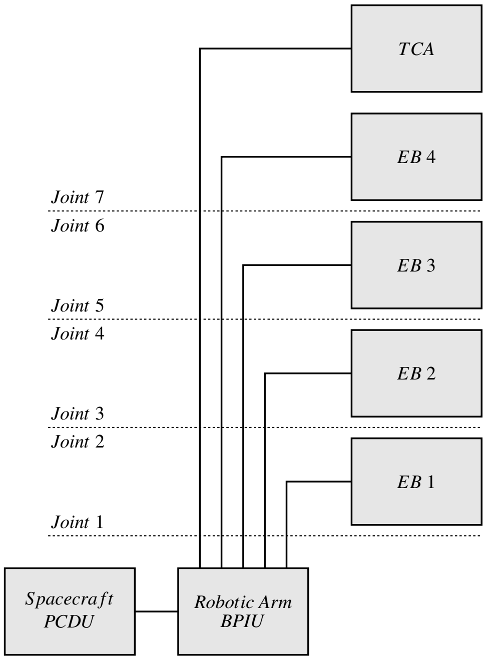

Figure 11. Structure of a parallel power distribution of CAESAR

joint RA is shown in figure 12. The dashed lines within the EBs of the figures illustrates the direct power transmission from one load to the other. Since the loads are not supplied individually by the BPIU as in the parallel variant, only one power harness is required in each hollow shaft.

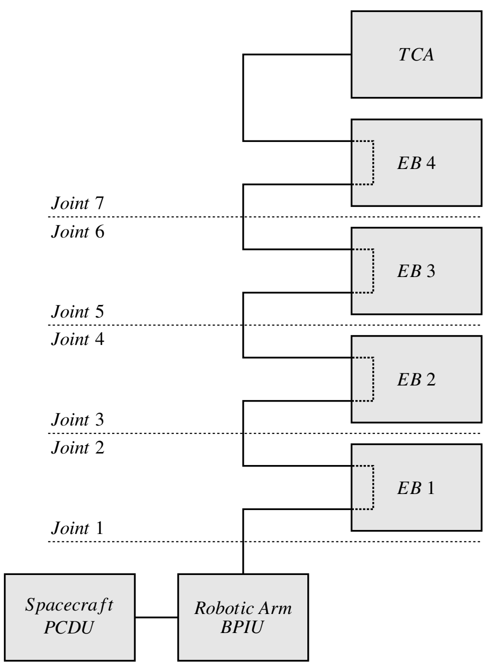

Figure 12. Structure of a serial power distribution of CAESAR

For this reason the power harness passing through the joint 1 from the BPIU to the EB 1 has to be capable of carrying the complete power of all EBs and the TCA. A serial power distribution scheme is already used in heritage systems such as the DLR LWR and MIRO robotic arm [9]. The resulting serial power harness can be realized either in the MSIR, the MSCR or the CMSS version. The different properties among these versions are part of the comparison in Table 3.

Holistic comparison of the individual solutions on power interfaces and distribution

To obtain a comprehensive overview of the characteristics of the possible combinations of MSIR, MSCR and CMSS together with a parallel or a serial power distribution, all of these have been combined in Table 3. This overview allows the subsequent comparison of the appropriate combination based on the advantages and drawbacks of the presented variants. There are six possible power interface and distribution solutions for the CAESAR arm.

The parallel power distribution requires more individual conductors than the serial distribution in any combination. With ten individual conductors the parallel version of the CMSS requires more than the serial version of the MSIR, which requires four individual conductors. The current load on the cables of the serial version is higher than the parallel version, which may require a larger cable cross-section. Consequently, the single cables are stiffer and the hollow shaft is filled to a higher proportion. The resulting current for the serial power harness is listed in the previous discussed Table 2. An additional advantage of the parallel distribution is that each EB is supplied individually and can therefore also be switched on or off individually. The transmitted power of one power harness corresponds to that of an EB according to Table 1 except for the TCA.

When comparing the power interface schemes, it is noticeable that the MSCR has the highest complexity compared to the others due to the required galvanic isolation. With parallel power distribution this galvanic isolation can be placed in the BPIU or in the EB. With the serial version the isolation has to be placed in the EB.
With the implementation of the CMSS fewer individual conductors are required in the power harness compared to the other variants. However, this has the drawback that the system supply can not be controlled independently of the motor supply and the complexity of the PSU circuit in the EB increase due to the higher voltage level.
MSCR and MSIR do not have the mentioned drawbacks. However, the combination of them together with the parallel power distribution of these require a large number of power harnesses through the first joint.

In conclusion, it can be said that for the comparison of the different combinations of power interface and power distribution schemes the different properties of the respective combinations bring multiple advantages and disadvantages. For a final decision on the optimal power distribution for CAESAR further boundary conditions and an assessment of the feasibility of the harness routing are required.

Hollow shaft occupancy and distribution selection

The analysis of the hollow shaft occupancy is critical to the feasibility of power distribution within the CAESAR RA. It is required that all necessary cables are routed through the hollow shaft without having an impact on the proper operation and the reliability of the robotic arm. To perform such a comparison, additional design conditions from CAESAR were used to calculate and to compare the hollow

Power Distribution Architecture Comparison		
	Parallel Power Distribution Architecture	Serial Power Distribution Architecture
MSIR	+ System can be powered up without motor supply. + Every EB can be individually powered up. - High amount of wires (4x4 for EB and 1x2 for TCA) in total. - System supply has to be galvanically isolated from motor supply to eliminate current loops.	+ Four power wires are required in the RA. + System can be powered up without motor supply. + Lower power harness weight compared to parallel power distribution. - System supply has to be galvanically isolated from motor supply to eliminate current loops. - Every EB of the RA is powered up at the same time. - In case of damaged cable posterior connected EBs in the chain fail in addition.
MSCR	+ System can be powered up without motor supply. + Every EB can be individually powered up. - High amount of wires (4x3 for EB and 1x2 for TCA) in total. - Electronics has to be robust against motor noise on combined return.	+ Three power wires are required in the RA. + System can be powered up without motor supply. + Lower power harness weight compared to parallel power distribution. - Electronics has to be robust against motor noise on combined return. - Every EB of the RA is powered up at the same time. - In case of damaged cable posterior connected EBs in the chain fail in addition.
CMSS	+ Two power lines per EB required. + Every EB can be individually powered up. - Moderate amount of conductors (4x2 for EB and 1x2 for TCA) in total. - Motor power supply is not individually controllable. - Electronics has to be robust against motor noise on supply. - Higher voltage ratings on PSU components required compared to separate system supply. - Higher conversion losses in PSU compared to separate system supply.	+ Two power wires are required in the RA. + Lower power harness weight compared to parallel power distribution. - Motor power supply is not individually controllable. - Electronics has to be robust against motor noise on supply. - Higher conversion losses in PSU compared to separate system supply. - Higher voltage ratings on PSU components required compared to separate system supply. - Every EB of the RA is powered up at the same time. - In case of damaged cable posterior connected EBs in the chain fail in addition.

Table 3. Comparison between power interface schemes in parallel and serial power distribution architectures ('+' indicates a positive aspect and '-' a drawback)

shaft occupancy.
For the CAESAR arm every system and harness, except for the heater and grounding, are designed to be cold redundant. Hence, two EBs (one nominal and one redundant) are needed for every two joints. Therefore eight EBs are necessary for one CAESAR arm consisting of seven joints. For this reason, a redundancy factor (r) is introduced to calculate the required number of cables and the total cross-section. This factor represents the number of systems to be supplied. For CAESAR this factor is two, for one nominal and one cold redundant system. The redundancy factor is an important component for the calculation of the individual cable harnesses through the hollow shaft. Equation 1 is used to calculate the cross-sections of the power harnesses for the subsequent comparison. The number of parallel harnesses (h) and the number of individual conductors in one harness (w) is determined by the combination of power interface and power distribution scheme. The variable $crosssection_{wire}$ represents the wire cross-section including the area of the conduction core and the isolation material around the core. Due to the torsion of the cables, only single cores are used for CAESAR's power harness.

$$crosssection_{harness} = r * h * w * crosssection_{wire}, \quad (1)$$

$$\begin{aligned} \text{where } r &= \text{Redundancy factor} = 2 \\ h &= \text{Number of parallel harnesses} \\ w &= \text{Number of individual conductors} \\ &\quad \text{in one harness} \end{aligned}$$

Based on system requirements, the smallest cross-section for one power cable is AWG 16. This is derived from the requirements on the mechanical strength and the required number of individual conductors in the cable. The cross-section of one AWG 16 cable used for CAESAR requires

$3.6\,\mathrm{mm}^2$ in total. This area includes the copper core size and the required isolation layers. Another design requirement is to keep the hollow shaft filled as little as possible. This ensures that correct operation is guaranteed and provides additional space for cables for cameras, gripper and further additional tools.
To ensure that the arm can also be checked for proper function during the transportation phase of the mission, it has to be ensured that the arm is properly fixtured. It is therefore necessary to activate the motor supply independently from the system supply. All these aspects are taken into account in the final selection.
The hollow shaft occupation is calculated in Table 4 for joint 1 to ensure the analysis of the worst case scenario. Joint 1 contains the largest number of power harnesses and individual connections in the entire arm covering all variations.

The following calculations of the required cross-sectional areas do not take into account the packing density of the different cable diameters. Every harness calculation is based on the area of the assembled cable including the required copper cores and their isolation layers. In each CAESAR hollow shaft there are $490\,\mathrm{mm}^2$ available for cable routing. A base configuration of harnesses is required independent of the power harness. It consists of $50\,\mathrm{mm}^2$ for the communication harnesses, $20\,\mathrm{mm}^2$ for the sensor wires, $15\,\mathrm{mm}^2$ for the heater supply, and $10\,\mathrm{mm}^2$ for the grounding braids that connects the chassis parts separated by the gears. The base configuration requires therefore a total area of $103\,\mathrm{mm}^2$. In addition, a parallel power distribution requires a set of power harnesses for the TCA. A total cross-sectional area of $14.4\,\mathrm{mm}^2$ in the first joint is required for this purpose. This connection is not required for the serial power distribution as it is part of the power harness for the EBs. A current carrying capacity up to 18.9 A is required for the complete power harness of the CMSS and for the common return line of the MSCR variant in combination with a serial power distribution. For this required current, an AWG 12 wire is selected which requires a total area of $7\,\mathrm{mm}^2$ in the hollow shaft.
The resulting hollow shaft occupation calculated in Table 4 shows that each power interface configuration requires less cross-section in serial than in parallel power distribution. In addition, the calculation shows that despite the difference in number of individual lines in the power interface combinations with the serial power distribution, there is only a negligible difference ($\Delta_{MSIR-CMSS} = 0.8\,mm^2$) in the power harness cross-section.

Based on the requirement for minimum occupancy of the hollow shaft, only serial power distribution systems remain for further consideration. This decision also takes into consideration, the drawbacks of the serial power distribution.
Furthermore, the CMSS can be excluded for the selection of the suitable power supply since it provides no possibility to control the motor supply independently from the system supply. Such a solution would be technically possible with an additional external control line, but it is not foreseen in the current system design. Despite the drawbacks of the MSCR variant in terms of EMI and the required high current carrying capacity of the common return line, the disadvantages of the MSIR variant are outweighed by the increased complexity of the required galvanic isolation between the system supply and the motor supply.
For these reasons, a serial power distribution scheme with a MSCR power interface is selected for CAESAR. This variant meets all the previously mentioned requirements.

<table>
<tr><th colspan="3">Hollow shaft occupancy of joint 1
in a full redundant configuration</th></tr>
<tr><td></td><td>Parallel Power Distribution</td><td>Serial Power Distribution</td></tr>
<tr><td>Hollow Shaft</td><td colspan="2">Available Area: $490\,\mathrm{mm}^2$</td></tr>
<tr><td>Base Configuration</td><td colspan="2">Communication: $r * 29\,\mathrm{mm}^2 = 58\,\mathrm{mm}^2$
Sensors: $r * 10\,\mathrm{mm}^2 = 20\,\mathrm{mm}^2$
Heater: $15\,\mathrm{mm}^2$
Grounding: $10\,\mathrm{mm}^2$
Sum: $103\,\mathrm{mm}^2$</td></tr>
<tr><td>TCA Power Harness</td><td>$2 * 1 * 2 * 3.6\,\mathrm{mm}^2$
$= 14.4\,\mathrm{mm}^2$</td><td>not applicable</td></tr>
<tr><td>MSIR Configuration</td><td>Power Harness:
$2 * 4 * 4 * 3.6\,\mathrm{mm}^2$
$= 115.2\,\mathrm{mm}^2$
Complete RA Harness:
Total: $232.6\,\mathrm{mm}^2$
Occupancy: $47.5\,\%$</td><td>Power Harness:
$2 * 1 * 4 * 3.6\,\mathrm{mm}^2$
$= 28.8\,\mathrm{mm}^2$
Complete RA Harness:
Total: $131.8\,\mathrm{mm}^2$
Occupancy: $26.9\,\%$</td></tr>
<tr><td>MSCR Configuration</td><td>Power Harness:
$2 * 4 * 3 * 3.6\,\mathrm{mm}^2$
$= 86.4\,\mathrm{mm}^2$
Complete RA Harness:
Total: $203.8\,\mathrm{mm}^2$
Occupancy: $41.6\,\%$</td><td>Power Harness:
$2 * 1 * 2 * 3.6\,\mathrm{mm}^2$
$+2 * 1 * 1 * 7\,\mathrm{mm}^2$
$= 28.4\,\mathrm{mm}^2$
Complete RA Harness:
Total: $131.4\,\mathrm{mm}^2$
Occupancy: $26.8\,\%$</td></tr>
<tr><td>CMSS Configuration</td><td>Power Harness:
$2 * 4 * 2 * 3.6\,\mathrm{mm}^2$
$= 57.6\,\mathrm{mm}^2$
Complete RA Harness:
Total: $175.2\,\mathrm{mm}^2$
Occupancy: $35.8\,\%$</td><td>Power Harness:
$2 * 1 * 2 * 7\,\mathrm{mm}^2$
$= 28\,\mathrm{mm}^2$
Complete RA Harness:
Total: $131\,\mathrm{mm}^2$
Occupancy: $26.7\,\%$</td></tr>
</table>

Table 4. Comparison between power supply schemes and their hollow shaft occupancy

7. CONCLUSION

This paper covers the various key aspects of designing a power supply and distribution network within the CAESAR Robotic Arm. For this purpose, existing heritage systems were analyzed and evaluated according to their supply solutions for the possible use in the CAESAR arm. System requirements of CAESAR and space mission requirements are taken into account. The presented comparison can be used as a basis for power supply decisions of future systems. For CAESAR, a serial power distribution in combination with a separate system and motor supply with a common return line is preferable due to the space saving properties and the lowered complexity of the overall system. The calculation of the power requirements of the overall robotic system as well as the selection of the power distribution consequently guides the development of the required BPIU.

Further research will cover an extended hollow shaft occupation estimation including the wire packaging properties of different wire diameters next to each other. The power sharing capability between the EBs during dynamic movements of the several joints based on representative trajectories will also be a part of future research within this area.

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