

Development of a Robotic Limb for Underwater Mobile Manipulation

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Abstract—This paper presents the hardware design and development of the AquaSimian limb, a 7 degree of freedom robotic limb for performing manipulation tasks typical to the subsea servicing industry. Tasks are performed through a supervised autonomy framework that makes efficient use of operator input, 3D scene reconstructions, automated motion planning, and parameterized behaviors. The limb must robustly interact with its environment to perform tasks such as turning a subsea valve or inserting a hot stab. The limb features high power density actuators and a 6 degree of freedom force torque sensor. A custom 3-function robotic gripper mounted to the force torque sensor allows dexterous yet robust interaction with underwater task panels. The system includes capabilities to detect and autonomously respond to any leaks or motor faults by disconnecting motor power when the system is in an off-nominal state and notifying the operator through LED lighting on the Light Lids that seal the actuator assembly housings. This highly capable robotic limb serves as a testbed for JPL development of technologies for autonomous operation of mobile manipulation systems.

I. INTRODUCTION

Robotic manipulation technology is widely used by the offshore oil and gas industry to perform intervention operations on subsea infrastructure by remotely operated vehicles (ROVs). The robotic manipulators found on intervention-capable ROVs typically rely on hydraulics to achieve motion and are controlled by topside operators through teleoperation [2]. This work presents the design and development of the AquaSimian limb, a novel all-electric 7 degree of freedom (DoF) robotic manipulator capable of supervised autonomous control. Unlike manipulators found on most intervention-capable ROVs, the AquaSimian limb is suitable for installation on inspection and light work class ROVs and can be incorporated into an autonomous intervention system. This highly capable robotic limb serves as a testbed for JPL development of technologies for autonomous operation of robotic manipulation systems in subsea environments.

At the onset on this project, a survey was performed of other 6+ DoF all-electric underwater manipulators both commercially available or previously reported. The ECA Group ARM 7E is a leading commercial example, but does not offer any motion planning automation required for supervised autonomy [1]. Non-commercial examples such as the SAUVIM project [7], the SAMUAI arm [4], and CRABSTER200 [5], all demonstrate interesting results

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Fig. 1. A CAD rendering of the AquaSimian underwater robotic limb.

by combining low-footprint all-electric manipulator designs with autonomous capabilities.

This work seeks to develop a new class of underwater robotic manipulator that achieves high power density with brushless electric motors and precision manipulation control through the integration of a 6-axis underwater force torque sensor. Additional features are included to allow field serviceability including modular actuators and housings, quick access Marman clamps for rapid limb disassembly, and actuator housing caps which provide visual feedback of the actuator and sealing status through pressure, temperature, and humidity sensors. This work leverages the previous development of RoboSimian, a mobile manipulation platform by the Jet Propulsion Laboratory (JPL) for the DARPA Robotics Challenge (DRC) [3]. The RoboSimian limb architecture was adapted for underwater deployment through the inclusion of environmental sealing and state monitoring of the actuator housings.

II. LIMB CONCEPT DESIGN

The initial limb concept architecture consisted of a modular, 7 DoF design incorporating distributed motor controllers. The kinematic layout of the limb features a 1 DoF shoulder with 3 linked roll-pitch elbow pairs. The same actuator size and gearing is used on every limb joint. Working within that

TABLE I
LIMB PERFORMANCE REQUIREMENTS

Parameter	Requirement
Depth	30 m
Limb Mass in Air	<50 kg
Limb Mass in Water	<20 kg
End Effector Payload (in air)	5 kg
End Effector Payload (in water)	20 kg
End Effector Torque	50 Nm
Actuator Rotation	+/- 360 deg
Sealing	Vacuum
Commutation	Absolute input/output
Compartmentalized Pressure Volumes	Per Elbow Housing

concept, the requirements outlined in Table 1 were generated to satisfy the goal of demonstrating standard intervention operations on a subsea panel.

III. LIMB HARDWARE DESIGN

A. Limb

The AquaSimian limb features 10 total degrees of freedom including a 3 function gripper and 7 degree of freedom modular limb. There are three elbow housings which each contain two orthogonal S-PRIME actuators and one shoulder housing which contains one S-PRIME actuator. Each elbow is connected through a static roll pitch adapter housing. The kinematic layout of the limb allows dexterous manipulation of elements in the limb's workspace. A modular approach was taken in designing the limb allowing the ability to swap sub assemblies in the field for rapid repair or reconfiguration. Each assembly is held on with a Marman Clamp on each end allowing the quick removal of a subassembly.

Power and communication pass along coaxially along the interior of the limb. At each roll pitch adapter housing, connections are routed through a sealed bulkhead allowing modular, independently sealed volumes. This leads to four separately sealed volumes which protect the limb in the event that one section of the limb sealing is compromised. The shoulder housing has an output to an underwater bulkhead connector for connecting the limb power and communication to ground support equipment via an underwater tether. For lab testing, the tether interfaces with a ground support equipment (GSE) box providing DC power and limb control through an Intel NUC. In a deployed configuration, the GSE box can be integrated onto an ROV for providing power and onboard computing for local motion planning.

The limb has a total reach of 1.25 m with a mass of 36 kg in air and 11 kg in water. This initial design is rated for 30 m depth based on testing constraints but could extend deeper upon further validation. For forceful interactions with its environment the limb is capable of carrying 20 kg in water mass (5 kg air).

To facilitate a variety of manipulations a few canonical arm poses are defined. The Pre-manipulation-1 pose affords a starting configuration for completion of tasks with the gripper axis aligned to the task panel surface normal. These tasks include such things as turning a valve or grabbing a handle.

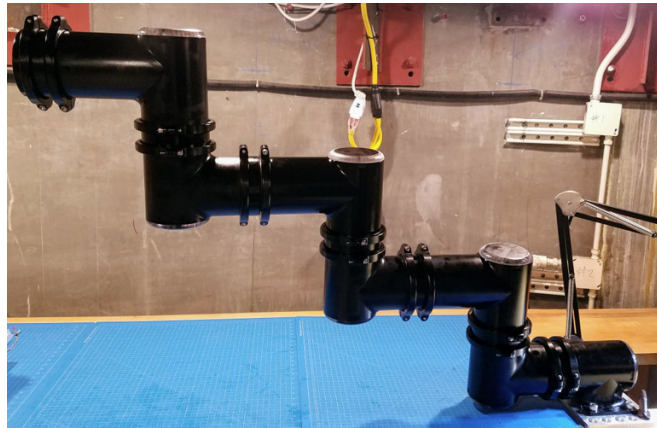


Fig. 2. The assembled limb deployed on a lab bench.



Fig. 3. The assembled limb in the Pre-manipulation-1 pose mounted to a test frame.

B. S-PRIME Actuator

The Submersible, Performance Rotary Integrated Modular Electric (S-PRIME) actuator is a custom brushless DC motor unit that features high power density and precision control. A frameless brushless rotor and stator provide rotation input to a harmonic drive of which the output generates torque for output to the limb. The harmonic drive enables a high gear reduction with zero backlash. Absolute encoders on the input and output of the drivetrain allow precise control of both the velocity and position of the actuator. A dynamic PTFE spring seal keeps the articulated joint dry against underwater submersion while static o-rings seal the actuator to the housing components. Each of the 7 S-PRIME actuators are identical allowing high torque at all joints of the limb and fast repair in the field if an actuator needs to be replaced. An individual actuator can generate a max torque of 285 Nm with a mass of 4.2 kg in air. The actuator electronics motherboard contains the motor control electronics and communicates over Ethercat to the main limb control software. This distributed motor control architecture allows

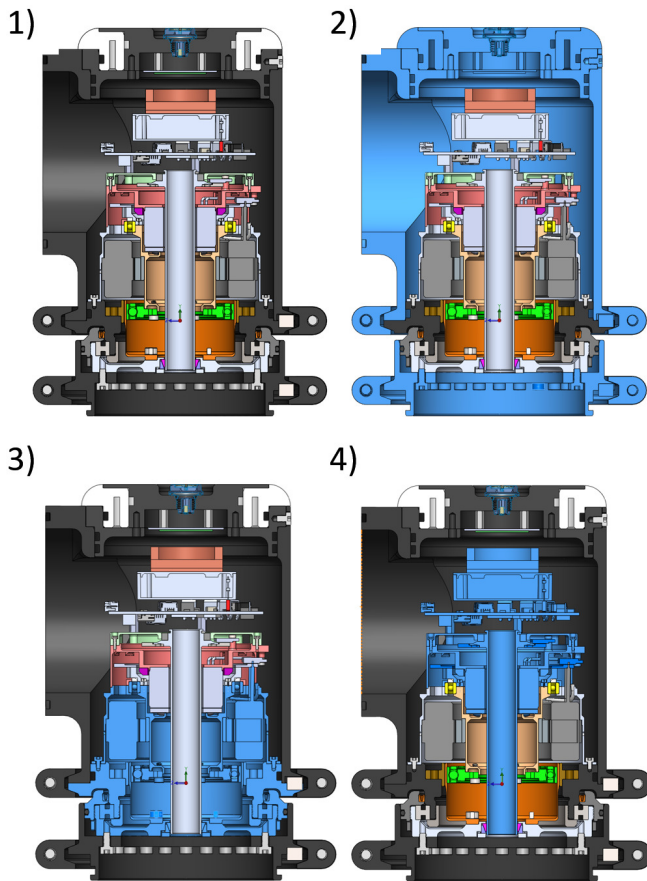


Fig. 4. 1) A cross section view of the shoulder housing containing one S-PRIME actuator, 2) The housing and output assembly of the actuator, 3) The S-PRIME drivetrain subassembly, 4) The S-PRIME sensing and control subassembly

TABLE II
S-PRIME ACTUATOR SPECIFICATIONS

Parameter	Value
Size	225 mm (length) X 120 mm (diameter)
Depth Rating	30 m
Weight (air)	4.2 kg
Weight (water)	1.6 kg
Max Torque	285 Nm
Max Speed	135 deg/s
Braking	220 Nm
Power	100 V, 14 A
Communication	Ethercat, RS-485

simultaneous control of many S-PRIME actuators across a single low power communication bus. The actuator can also report its status over serial to the Light Lid motherboard for visual display of the motor condition and any detected fault warnings. The Light Lid displays this information to the operator using its LEDs, which are externally mounted on the housing.

C. End Effector

A 6-axis force torque sensor mounts between the limb and the gripper. The output of the force torque mounting plate allows swappable end effectors for mission dependant

TABLE III
CALCULATED LIMB LOADS

	Air (Nm)	Water (Nm)
Maximum Load on Joint	264	298
Motor Torque	2.75	3.1
Brake Torque	0.99	1.12

TABLE IV
SELECTED COMPONENT RATINGS

Component	Load Rating (Nm)
Marman Clamp	285
Frameless Motor Torque at 14 A	3.57
Brake Hold Torque	1.8

configuration. At the end of the limb is a 3-function gripper with four removable fingers allowing dexterous yet robust interactions with subsea interfaces. The fingers are driven by Spiroid gears enabling high torque output and non-backdrivable motion. The outer fingers rotate together while each inner finger is independently driven. This allows the gripper to hold an object and articulate an independent finger, which is useful for operating underwater power tools. This gripper allows a higher fidelity of autonomous control and task panel interaction than a 1-function gripper does.

IV. ANALYSIS

Analysis and testing was performed to ensure the S-PRIME joints were adequately sized relative to the limb mass and payloads. The full limb extension posture was analyzed to determine the maximum torsional load on a limb joint in air and water. These loads were then used to calculate the required torque of the Marman clamp interface, brushless motor, and brake. These required torques were compared to the selected components in Table 4. Calculations assume 60% efficiency which combines harmonic efficiency and dynamic seal running torque. The end effector mass was not included in load calculations.

Analytical values for the Marman clamp interface holding torque and the maximum actuator torque output were empirically validated through load stand testing. After testing showed that the Marman clamp interface was undersized relative to the maximum torque, a titanium face key feature was added along the interface to prevent slippage in high load cases and to provide a clocking feature for assembly.

V. DEMONSTRATIONS

To validate the limb design a number of demonstrations were performed both in the lab and during a field trial at the Los Angeles harbor. In the lab, testing was performed both in the air and in a water tank. During initial validation, the limb was commanded to a variety of canonical poses, orientating a fiducial on the gripper towards the perception suite for hand eye calibration. These poses also demonstrated limb motion across its workspace.

Tests were performed to validate robust interaction with a task panel typical to the subsea industry. A welded frame



Fig. 5. The AquaSimian Limb mounted to a test frame with a subsea task panel for field testing.

was developed to mount a task panel within the workspace of the limb. The task panel contains features such as a hot stab port for a T-handle tool, a rotary valve, and a pressure gauge. The first demonstrated task was automated rotation of the valve using supervised autonomous commanding of the limb poses through an Operator Control Unit (OCU). The operator was able to visualize the task panel location and limb pose in a rendered 3D environment. Commands were issued to the limb and a planner computed the joint motion trajectories for completing the cartesian space moves. This type of simulation environment was inspired by the interface used by Rover Planners for sequencing commands to the Curiosity Rover for the Mars Science Laboratory Mission [6].

A field test at the port of Los Angeles demonstrated the successful completion of the valve turn task with the limb deployed in the ocean and a top-side operator controlling the limb over the operator interface. The limb was attached to the submersible task panel frame and lowered into the ocean until the frame was submerged. On the surface, an operator sent commands to the limb via the Operator Control Unit (OCU) to perform the valve turn. High level commands (e.g. go to pre-manipulation-1 pose, approach offset position, rotate joint 7 90 degrees, retract) were used to complete this task.

VI. FUTURE WORK

The currently installed end effector is a simple static two prong interface for completing the valve turn task. A 3 function gripper as described has been designed but is currently in fabrication. Upon completion of the assembly,

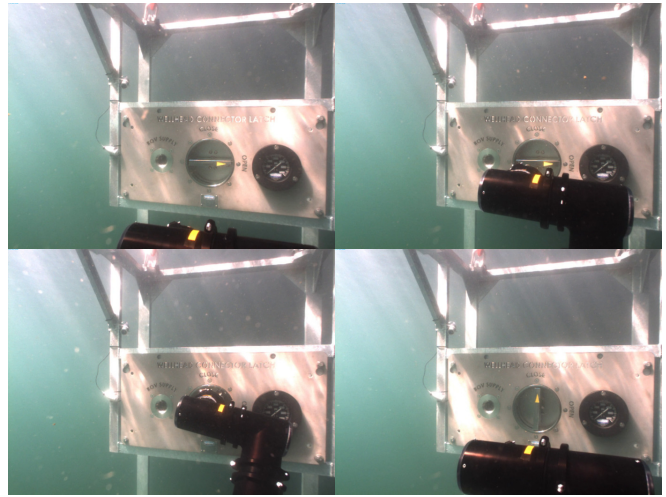


Fig. 6. The limb demonstrating a valve turn while deployed in the Los Angeles harbor.

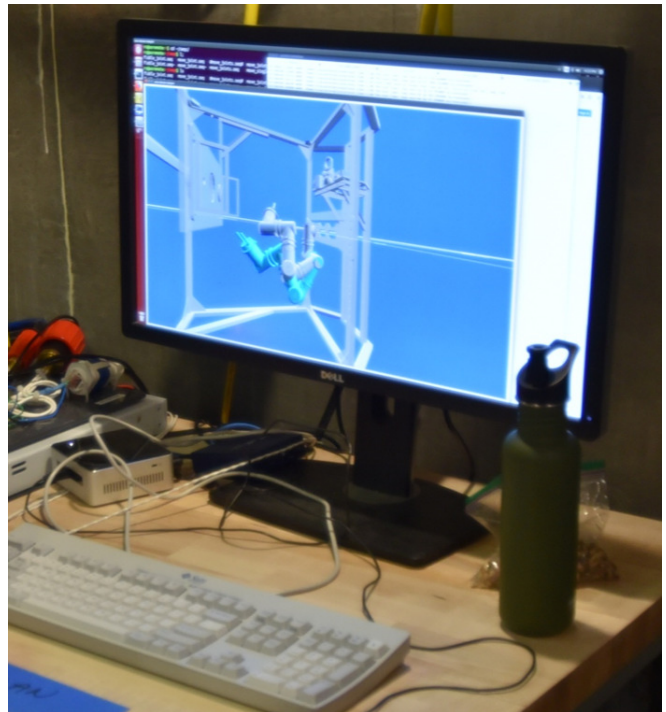


Fig. 7. The limb operator utilizing the Operator Control Unit (OCU) to command and visualize motion.

validation of the gripper will occur along with integration of the new gripper onto the limb. This new gripper will allow additional demonstration of tasks with the limb such as insertion of a T-handle into a hot stab port on the task panel. The gripper will also be able to wield a variety of underwater tools such as a cutting saw or drill. A demonstration of supervised autonomous cutting was demonstrated by Robosimian during the DARPA Robotics Challenge using a similar gripper design referred to as the Cam Hand.

Each joint includes a housing cap with a potted LED strip for state indication of the actuator and display of any



Fig. 8. The Light Lid warning of a detected leak through visual display of a red indicator light.

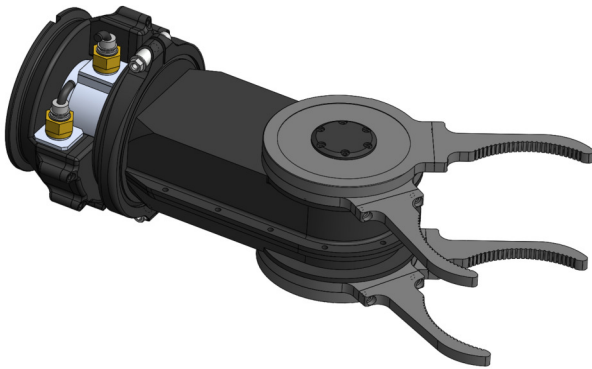


Fig. 9. The 3 DoF end effector design featuring interchangeable fingers and a 6-axis force torque sensor.

safety faults. The current implementation monitors pressure state and displays an error if a rapid pressure change occurs,

indicating a potential leak. Future work will involve programming the motor controllers to interface with this housing light for display of state. These displays will include whether an actuator is braked, in motion, or faulted. Additional safety warnings will include excessive thermal conditions or a spike in moisture content.

VII. CONCLUSION

In this paper we have described a fully electric underwater robotic limb capable of robust interactions with an underwater task panel. The design is highly modular for efficient serviceability with high power density brushless DC motors allowing performant operations on an underwater task panel. Leveraging the Aquasimian Limb with our work on a 3D scene reconstruction perception suite enables the development of supervised autonomous intervention operations on subsea infrastructure.

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