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KINEMATIC AND TECHNOLOGICAL ASPECTS OF DESIGNING AN ENERGY-EFFICIENT UNDERWATER MANIPULATOR FOR INSPECTION ROVS

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Annotation: The article justifies the application of self-locking worm gears and hybrid additive manufacturing (FDM and SLA) to overcome the functional limitations of light inspection ROVs. The transition from primitive single-link grippers to multi-link articulated manipulators is hindered by the backdrivability of classical gears, causing power deficits and motor overheating. The proposed integration of mechanical self-locking ensures passive load holding without static energy consumption.

Additionally, the use of hermetic air microcavities via FDM infill adjustment compensates for the mass of metal components, achieving local neutral buoyancy. These solutions minimize the material consumption and cost, enabling budget underwater vehicles to perform full-fledged contact operations.

Keywords: Underwater robotics, manipulator, worm gear, mechanical self-locking, neutral buoyancy, additive manufacturing, ROV.

Introduction. Modern monitoring of underwater infrastructure – fiber-optic communication lines, power cables, and ship hulls – increasingly requires the performance of contact inspection operations. While an onboard video camera is sufficient for preliminary visual inspection, assessing the corrosion of welded seams, installing ultrasonic thickness sensors, or removing bottom sediments requires a fully functional end-effector: an articulated manipulator.

However, a functional dead end is observed in the accessible segment of

small-sized equipment.

Mass-produced commercial platforms (e.g., Chasing, QYSEA) are equipped with primitive single-link grippers with one degree of freedom (1-DOF). Such a mechanism is essentially a static rod with a claw: it lacks movable joints for the spatial orientation of the tool relative to curved surfaces or buried cables [1]. At the same time, multi-link manipulators of the industrial class (Work-Class ROV) have excessive mass, metal consumption, and cost, which is many times higher than the price of a light carrier [2].

A contradiction arises between the need for precise spatial reorientation of the working body and the high cost and mass-dimensional characteristics of existing solutions. The purpose of this work is to design an affordable multi-link underwater manipulator with passive position fixation, capable of performing spatial positioning of sensors without excessive energy consumption.

A key problem in designing small-sized underwater manipulators is ensuring the rigid fixation of the links' spatial position under the influence of external loads. During contact operations – pressing an ultrasonic sensor against a ship's metal side, holding a lifted communication cable, or resisting bottom currents – significant static and dynamic moments act on the end-effector and articulated joints.

Most serial small-sized actuators use multi-stage planetary or spur cylindrical reducers. They are characterized by high back drivability: an external moment applied to the output link easily overcomes the internal resistance of the engagement and rotates the motor shaft in the opposite direction [3].

To maintain a given system configuration, the control system is forced to continuously supply current to the motor windings to create a holding torque. Under underwater operating conditions, this approach leads to two critical consequences: first, intense depletion of the battery, which significantly reduces the duration of the inspection mission; second, thermal overload of the drives.

The placement of motors in sealed capsules prevents free air convection, and continuous static current causes overheating of the windings, accelerated insulation degradation, and a risk of node failure [4].

Table 1

Risk of node failure [4]

Characteristic	Planetary Gearbox	Worm Gearbox (Proposed)
Backdrivability	High	None (Self-locking)
Holding Current (at 1 Nm load)	≈ 1.5 – 2.0 A (continuous)	0 A (passive fixation)
Static Heat Dissipation	Critical in a sealed capsule	Zero
Number of stages for i≈40	2-3 stages	1 stage
Shock Load Resistance	Low (risk of tooth breakage)	High (load distribution over several threads)

Note: Holding current data are typical calculated values for brushless servo drives of the NEMA 17/23 class used in light ROVs [4, 5].

As an effective mechanical solution to this problem, the integration of worm gears into the kinematic pairs of the manipulator's rotary joints is proposed. The main design advantage of a worm gear is the possibility of realizing the effect of mechanical self-locking. It is achieved when the lead angle of the worm is less than the reduced friction angle of the contact pair materials ($\gamma < \varphi$) [5]. Under this condition, the transmission becomes strictly non-reversible: kinematic movement is transmitted exclusively from the driving worm to the driven worm wheel. Any external moment applied to the manipulator link is compensated by normal reaction forces and friction in the engagement, making spontaneous rotation of the input shaft impossible.

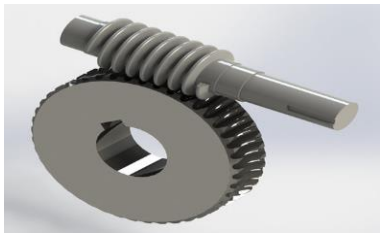


Fig. 1. A 3D model of a worm gear, illustrating the principle of non-reversible meshing [11]

This allows for a mode of passive position fixation: after the working body reaches a given point in the trajectory, the power supply to the servo drive is completely turned off [6]. The manipulator reliably holds the load purely due to the mechanical properties of the reducer, without consuming electricity or generating heat.

Furthermore, a worm gear provides a high gear ratio (i = 30 … 50) in a single stage, which significantly minimizes the overall dimensions of the joint housing compared to bulky multi-stage schemes. The design of the rotary unit is supplemented by sliding thrust bearings, which absorb longitudinal axial forces along the worm shaft, completely unloading the bearing supports of the electric motor itself.

Traditional subtractive manufacturing of underwater joints (CNC milling of corrosion-resistant alloys) is accompanied by a low material utilization rate (0.2 … 0.3), high cost, and dependence on centralized supplies. As a waste-free and resource-saving alternative, On-Demand Manufacturing technology implemented through hybrid additive forming is proposed [7].

Stereolithography (SLA) with engineering photopolymers (Tough/ABS-like) is used for precision moving components – the worm, worm wheel, and seating grooves for radial O-ring seals. Due to high forming accuracy and complete isotropy, the photopolymer provides minimal tooth profile roughness and an absolute absence of interlayer capillary pores, preventing water leakage under hydrostatic pressure and abrasive wear of the sealing collars [8].

Fused Deposition Modeling (FDM) with thermoplastics (PETG, PA-CF) is applied for the outer shells of the links and brackets. This choice is due to the high impact toughness of the material, which protects the structure from brittle fracture upon contact with the bottom or an overgrown ship hull [9].

A significant engineering advantage of FDM technology is the ability to solve the problem of static gravitational balancing of the links. The presence of internal metal components (motors, bearings, shafts) creates negative buoyancy and undesirable overturning moments in the joints. By spatially adjusting the percentage and topology of the internal infill (e.g., hermetic closed gyroid-type cells), calculated compensation for the mass of metal parts is achieved. This ensures the local neutral buoyancy of each manipulator segment without installing bulky external syntactic foam floats [10].

The proposed approach eliminates harmful chemical metalworking processes,

minimizes the carbon footprint, and reduces the cost of manufacturing nodes by an order of magnitude compared to industrial analogs.

Table 2

Comparison of material properties for hybrid additive forming of underwater nodes [9]

Property	FDM (PETG / PA-CF for structural shells)	SLA (Tough / ABS-like Resin for gears and seals)	Milled Aluminum (6061-T6 – classical method)
Izod Impact Strength	≈ 7 – 10 kJ/m² (High)	≈ 3 – 5 kJ/m² (Moderate)	> 20 kJ/m² (Very high)
Interlayer Permeability under pressure	Possible (requires 100% infill or coating)	None (Full isotropy)	None
Surface finish for O-rings	Low (risk of elastomer wear)	High (Ra < 1.0 μm)	High
Local Buoyancy Control	Yes (via Infill adjustment)	No (solid infill)	No (requires external floats)
Material Utilization Rate	≈ 95% (Waste-free)	≈ 90% (Waste-free)	≈ 20-30% (Significant chip waste)

Note: The physical and mechanical properties of polymers are averaged based on the specifications of additive manufacturing material manufacturers (e.g., Polymaker, Formlabs) and studies of polymer tribology [8, 9].

As a result of the analysis and engineering synthesis, the concept of creating an energy-efficient multi-link manipulator for the segment of light remotely operated vehicles (ROVs) has been justified. It has been established that the transition from primitive single-link grippers to articulated systems for spatial positioning is hindered by the back drivability of classical gear transmissions, which leads to a power deficit and thermal overloads of the drives.

It has been proven that the integration of non-reversible worm gears with the implementation of mechanical self-locking into articulated joints ensures the rigid passive fixation of the working body in a given position. This radically reduces the static energy consumption of the system, shifting the holding of the load (resisting currents, the weight of cables, or reactive forces from pressing sensors) from the electric motors' power supply to the friction forces in the engagement.

Conclusion. The feasibility of using hybrid additive forming (FDM + SLA) instead of traditional subtractive metal processing has been substantiated. The

distribution of technologies – SLA for precision isotropic transmission parts and seals, and FDM for power structural shells – ensures high strength and complete waterproofing of moving parts. Furthermore, the use of air microcavities by adjusting the internal infill of FDM components allows for the compensation of the mass of metal shafts and drives, ensuring local neutral buoyancy of the manipulator links without additional mounted ballast. The proposed solutions minimize the material consumption and cost of the design, expanding the functional capabilities of budget inspection ROVs for performing full-fledged contact operations.

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