Marine Propulsor based on a Three-Degree-of-Freedom Actuated Spherical Joint

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ABSTRACT

We have designed and manufactured an innovative *spherical joint* mechanism with *three actuated degrees of freedom*, aimed at re-examining sculling as a potential propulsion technology with high efficiency and maneuverability. In addition, the mechanism might also enable propellers with directional thrusting capability.

A *parallel* architecture was chosen for this type of mechanism in order to enable *rigidity* as well *high actuation frequencies and amplitudes*. Indeed, as the motors are fixed, inertial forces are lower than for a *serial* robot. The resulting spherical parallel mechanism (SPM) with coaxial shafts was designed and manufactured with the following specifications:

- Fixed center of rotation (spherical joint)
- Working frequency ~ 2.5 Hz under charge
- Unlimited rotation about main axis
- Arbitrary motion within a cone of ± 60°

The equations for the inverse kinematics of the mechanism have been established and can yield the trajectories of each actuator for any desired motion applied to the oar or blade.

Keywords

Marine, propulsor, spherical, parallel, joint

1 INTRODUCTION

Most human-based hydrodynamic propulsion systems make use of a spinning set of blades (a *propeller*), with a configuration that is fixed in the rotating frame. The principle of the propeller as a propulsion element was not invented until very late in the human technological culture (early nineteenth century) and has not changed significantly in the last 150 years. Its working principle is an extension of *sculling*, a rowing technique based on the *lift force generated on an oar* and used by rowers on Venetian gondolas as well as a some marine animals, such as penguins (Noca et al. 2010, Noca et al. 2011, Noca et al. 2012). The propeller revolutionary breakthrough was to replace the sculling alternating movement with a continuous rotary motion (a movement that is easy to generate with human technology), the oar being replaced by the blades of the propeller. While mechanical design was greatly simplified with the introduction of a simple rotating device, maneuverability (and probably hydrodynamic efficiency as well) was certainly impaired.

We have designed and manufactured an innovative *spherical joint* mechanism, which, by definition, is characterized by *three degrees of freedom* and a *fixed center of rotation* (Sudki 2011). It is *actuated* and aims at re-examining sculling as a potential propulsion technology with high maneuverability and improved hydrodynamic efficiency, as observed in Nature (Bandiopadhyay 2009).

2 SPHERICAL JOINT AS SHOULDER

The spherical joint is a mechanical representation of an animal (penguin, for instance) shoulder joint. It enables three degrees of freedom (DOF) represented by the three Euler angles (Figure 1), which, for a penguin flipper, correspond to pitching or blade angle of incidence (α), flapping or upstroke-downstroke angle (β), and rowing angle (γ). Although penguin swimming is still poorly understood (Noca et al. 2012), the following remarks can be made. The upstroke-downstroke movement along with a proper variation of the pitching angle enables the animal to generate thrust through lift forces on the foil. The purpose of rowing motion (which is what human swimmers as well as rowers use) is yet to be fully comprehended, but it is likely that it is not used for paddle-type (drag-based) propulsion. One suggestion is that an appropriate interplay between the Euler angles (flapping, pitching, and rowing) allows the animal to take

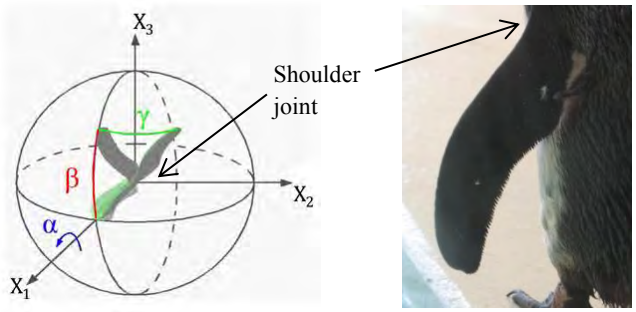

Figure 1: Euler angles for a shoulder-based spherical joint.

advantage of *unsteady* vortical structures generated by the flipper motion itself, and, thus, increase the lift (and thrust) forces on the wing.

In the present device, the spherical joint, unlike an animal shoulder joint, has the additional property of allowing unlimited rotational range about the main shaft axis. This feature might enable conventional propellers with directional thrusting capability. The idea of using such a spherical joint as a vector thruster for autonomous underwater vehicles has already been explored theoretically by Cavallo (2003). However, the proposed device was never manufactured.

Our immediate goal is not to deliver a final product, but to present a first attempt at emulating a *compact spherical joint* (shoulder) *capable of transmitting high torques*. A quick examination of the extremely sophisticated, yet simple, muscle structure of a swimming animal shoulder is an indication that our device is only a first step in that direction. If a first attempt is made to implement such a technology on a marine vessel, it will most likely be on a platform requiring a high level of maneuverability. As a matter of fact, *two shoulders would suffice to generate six degrees of motional freedom* (translation and rotation), which typically require six independent rigid thrusters. An example is the underwater testing of space structures for simulating microgravity environments (Swiss Space Center CleanSpace One project).

3 ROBOTIC MECHANISMS

Robotic systems can be subdivided into two main classes: *serial* robots and *parallel* robots.

Serial robots are generally considered poly-articulated system inspired by the human arm. The main feature of serial robots is a kinematic chain in open loop (Figure 2). They are found mainly in the industry and are generally used in areas such as automotive manufacturing (welding, paintwork), industries where human presence is not possible (foundries or nuclear plants), food processing (goods transported over short distances, put in position for packaging). Such robots usually have six degrees of freedom, 3 translations and 3 rotations. Most serial robots consist of an actuator for each axis of motion.

By definition, a parallel manipulator is a closed kinematic chain for which the terminal body is connected to the base by several independent kinematic chains (Figure 2). The early development of parallel mechanisms dates back to French mathematician Cauchy (1813). However, it was not until the middle of the 20th century that the first practical designs of parallel architectures were implemented onto actual machines, in particular with the hexapods developed by Gough in the 50s and Stewart in the 60s (Merlet 2008).

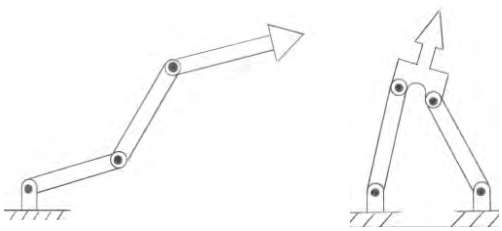

Figure 2: Left: serial mechanism; Right: parallel mechanism.

The main advantage of a parallel architecture is that it allows large accelerations due to the very low inertia of moving parts and a high rigidity of the mechanism. Indeed, the main feature of this type of manipulator is that the actuators are attached to the frame. The actuators are not moving parts of the mechanism as in the case of serial robots. In addition, due to higher rigidity, inaccuracies in the movement and/or orientation of the tool are significantly reduced. Indeed, for a serial robot, the inaccuracies are the direct result of gap clearances and lower rigidity in the links. This type of manipulator can, therefore, move and/or guide the tool at high speed while maintaining high accuracy. The two most popular parallel architectures are the hexapods (Gough-Stewart platforms) and Delta robots, invented by Clavel (1991), and are mainly designed for the following tasks: high-speed sorting; accurate orientation of components (Gosselin & Angeles 1989, Bonev et al. 2006); multi-axis CNC machines; medical robots; flight simulators. One of the drawbacks of parallel manipulators is the control system: indeed, the kinematics and inverse kinematics don't have a simple solution. Moreover, the work area is relatively limited because of the size of the entire robot.

4 SPHERICAL PARALLEL MECHANISM (SPM)

4.1 Architecture and kinematics

With reference to the classification scheme of parallel mechanisms by Cavallo (2003), it was decided to use a *symmetrical* parallel mechanism. Indeed, the equations of direct and inverse kinematics are extremely complex and require significant resources of numerical calculations for *asymmetrical* parallel manipulators.

By definition, a system is called *symmetric* when a parallel architecture obeys the following three rules: 1. the number of links between the fixed part and the movable part of the mechanism is equal to the number of degrees of freedom of the mechanism itself; 2. all links have the same architecture (in other words, the type and number of joints are identical for each link); 3. the number and location of the drive links are the same for each member.

There are several types of spherical parallel mechanisms, with 3 to 6 DOF. With a view to developing a

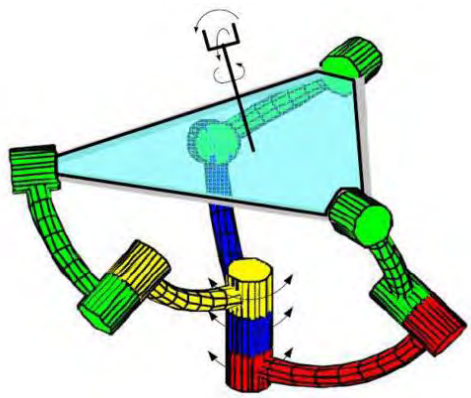

Figure 3: Representation of a SPM with coaxial shafts (from Bai & Hansen 2007).

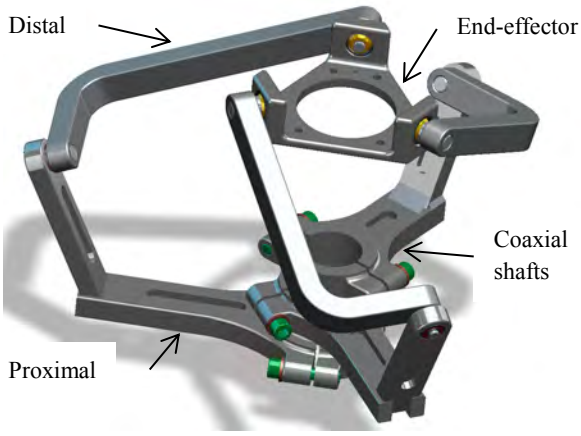

Figure 4: Nacelle held by three distals and proximals to the shafts.

manipulator specifically dedicated to the representation of a *shoulder joint* (as for a penguin), the number of DOF of the manipulator corresponds to the number of DOF required to reproduce the movement, that is to say 3 DOF.

The working environment of the device imposes some conditions on its architecture. In particular, the mechanism (without the blade) should not interfere with the flow and needs to be designed as to be inside a hull or above a water surface.

Because of these requirements, the architecture based on the work of Asada (1985) and Cavallo (2003) has been chosen. It is a SPM with three coaxial shafts (Figure 3). The mechanism is composed of three elements of two kinematic chains, three pivot links per chain, or 9 in total. The three links are connected to the frame and to the *end-effector* (Figure 4), and each of the links ends in pivot joints. Each of the links is comprised of two parts, a *proximal* and *distal* (Figure 4).

However, such a mechanism makes the kinematics indeterminate. Indeed, the law of Chebychev-Grübler-Kutzbach (Craig 1989) sets the number of degrees of freedom of a mechanism. It is defined as:

$$N_{DOF} = 6 \cdot (k_s - 1) - \sum_{i=1}^{n} M_i + h_s$$

where N_{DOF} is the number of degrees of freedom of the mechanism, k_s the number of solid components in the mechanism, n the number of links, M_i the number of kinematic unknowns for each linkage, and h_s the degree of hyperstatism in the mechanism. In the case of a spherical parallel mechanism, the number of kinematic loops is 2 and the number of degrees of freedom of the mechanism is then 3 (because we need a 3 DOF mechanism). With the current settings, with only pivot links, we obtain:

$$N = 3(\textstyle\sum_{i=1}^{3} k_i) - 6 \cdot 2 = 3 \cdot (1 + 1 + 1) - 12 = -3$$

This yields a mechanism with an indeterminacy of order 6. In order to meet the specifications regarding the number of DOF of the mechanism, it is necessary to replace the three pivot connections that bind distals to the end-effector by ball-joint type of links (Figure 4), which gives:

$$N = 3\left(\sum_{i=1}^{3} k_i\right) - 6 \cdot 2 = 3 \cdot (1 + 1 + 3) - 12 = +3$$

The specifications in terms of mobility are thus met. In addition, this architecture has the advantage of placing the drive portion (motors) on one side of the joint. Such a geometry enables the use of a compact motor.

A Matlab program was written to solve for the inverse kinematics equations (Gosselin et al. 1994), and provides theoretical angular positions for each of the gears and actuators (Figure 5).

4.2 Singularities

By definition, a manipulator configuration is called *non-singular* if the following two conditions are met:

1. The actuator speed determines the speed of the whole mechanism, including the speed of the end-effector.

2. The controlled speed of the end-effector determines the speed of the whole mechanism.

Otherwise, we speak of a singular configuration. In general, the singular loci occur when at least two axes are collinear. It is, therefore, necessary to avoid these configurations or move quickly through them, while

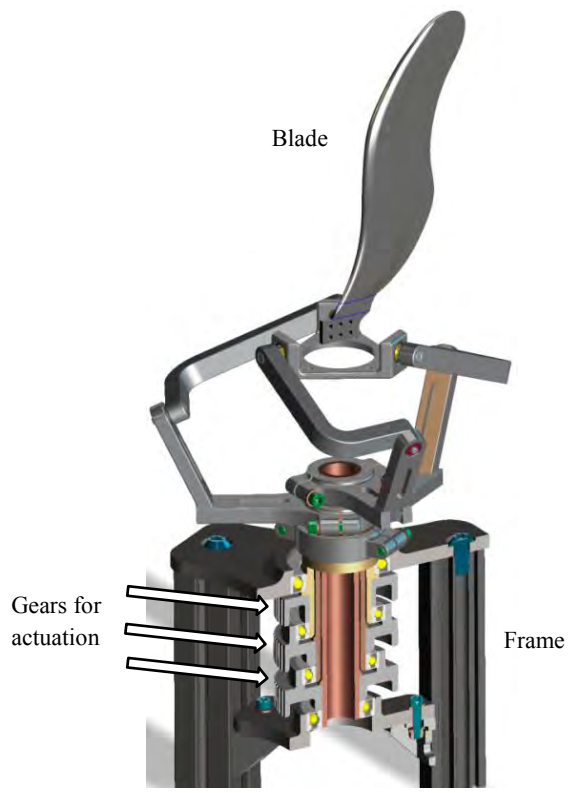

Figure 5: Complete mechanism with blade and gears.

keeping in mind that the behavior of the mechanism at these locii is uncontrollable.

We define the *workspace* as the volume accessible by the robot tool (blade). It mainly depends on the geometry of the architecture and the type of joints (with or without stops). The volume can take simple shapes such as a sphere or a cuboid, but also very complex shapes.

Only singularities of Type II, that is singularities that appear within the workspace (Bai & Hansen 2007), have been studied in this work (Type I singularities are those that occur on the workspace boundary). When the manipulator is in a configuration of this type, the end-effector gains additional degrees of freedom and is, therefore, uncontrollable. The mechanism then loses its rigidity. In other words, when in a singular configuration, even with the drive axles locked, the platform is loose. It can be shown that the workspace is free of singularities of type II. Our device is, therefore, free of Type II singularities.

5 MANUFACTURING AND ASSEMBLY

Due to the low fatigue strength of aluminum, stainless steel was chosen for the most stressed parts. To avoid galvanic interactions (aluminum-stainless steel) that may cause gripping, it was decided to use stainless steel for all joint components. However, some components of the engine are, themselves, made of aluminum and stainless steel, including the motor support and crankcases. Since the whole motor assembly is stationary and removed on rare occasions, a combination aluminum-steel was allowed.

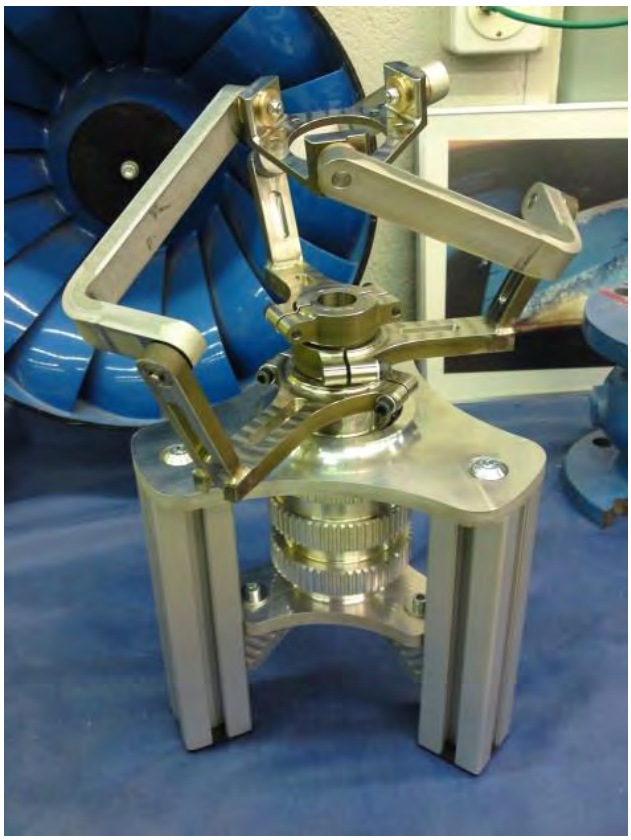

Figure 6: Manufactured spherical joint.

To reduce mechanical stresses at the end-effector joints (caused by hyperstatism), links with gap clearances are used at the joints. The final manufactured product is shown in Figure 6.

6. OPERATION AND PERFORMANCE

The whole mechanism is driven by three gears connected to the coaxial shafts of the assembly. The gears will be driven (via belts) by brushless servomotors with gearheads allowing up to 2.5 Hz transients. The motors can be programmed to provide the desired kinematics. The device allows an unlimited rotational motion within a cone of ± 60°.

In the near future, the device will be tested in an actual hydrodynamic environment (towing-tank). A force balance will be installed onto the end-effector and linked to the blade. Quantitative 3D PIV flow measurements (with TSI V3V camera system) will be performed. The *hydrodynamic* performance and efficiency of the propulsive device will thus be measured. In addition, the device will also be tested in pure rotation mode, in order to probe the idea of an orientable thrusting device. While the mechanical design is more complex than for a rotating propeller, it is expected that the *hydrodynamic* efficiency will be quite high, as already observed in the past with biological and biomimetic propulsion devices - see, for instance, the review by Bandyopadhyay (2009).

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