System Integration and Fin Trajectory Design for a Robotic Sea-Turtle

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Abstract— This paper presents a novel underwater robot based on biological locomotion principle. A robotic platform imitating sea-turtle fin propulsion is described and tested. As fin locomotion is a novel and complex research area, basic control concepts are analyzed and implemented. Based on a simulation, a fin-trajectory morphing control strategy is developed in order to control the robots roll, pitch and yaw rates, thus allowing the robot to follow a given vector. Absolute position control or depth control, however, is not yet implemented. The paper concludes with the presentation of a working system that demonstrated motion capabilities in air as well as the first dive test in a swimming pool.

I. INTRODUCTION

This paper describes the design and implementation of an underwater robot. Its main feature is the bio-inspired design and propulsion similar to sea turtles. The following paragraphs give an overview of this contribution and the context under which it was developed.



Fig. 1. Graphical representation of the naro-project history starting with the student project in 2008 following on the development of a 3DOF fin actuation system. The final naro-tartaruga was built in 2012.

Under the name naro-nautical robot a large scale student project was conducted at the ASL Zurich, Swiss Federal Institute of Technology. During this project in 2008-2009, a tuna-shaped robot was designed and successfully tested. This robot marked the first milestone for flapping fin robots at the Institute. Not only did it raise public interest but it also helped to define goals for future projects.

The main motivation for building flapping fin underwater robots is clearly the fluent and aesthetic locomotion of marine animals. There is no abrupt change in motion, no stop and restart. Fin beats are fluent and continuous. Many researchers got interested in this flowing motion of fins. Be it the tail fin of a fish or the flippers of a turtle. Different fin motions and fin shapes are individually optimized by nature for their specific purposes. Flexibility, agility, efficiency, high speeds, and endurance are some of the main attributes that can be used to describe fin-locomotion concepts.

II. TOWARDS A ROBOTIC SEA-TURTLE

A. Fin Actuation Mechanism

Following the development of our robotic fish, and to allow the use of sensors on a robotic platform based on fin propulsion, the general concept had to be revised. A flexible and moving body may be optimal for drag reduction [1], but causes some crucial technical problems in terms of sealing, mechanical endurance and sensor placement. The wish for a new robotic system with a rigid body was born. The concept of flapping fin propulsion, however, should be kept. Literature research about turtle locomotion provided interesting facts about how sea-turtles swim and defined the main features that a fin propulsion mechanism should incorporate.

However, the flipper trajectories of turtles are multidimensional. A three degree of freedom (3DOF) fin actuation mechanism was thus developed [2]. This mechanism would allow a flipper motion close to the natural sea-turtle locomotion. Studies of already existing robots revealed that no system so far was able to control a fin in three degrees of freedom.

Figure 1 shows a rapid prototype model of the fin actuation mechanism developed in 2011. This actuator is based on a differential gear with an added third dimension of rotation. The flipper can be actuated independently in all three dimensions: *flapping* (up-down) *feathering* (forward-backward) and *pitching* (fin rotation along fin axle).

B. Biological studies

The fact that sea-turtles have existed on our planet for millions of years and are endangered now is just one reason, why the focus fell on these animals. Their fluent and efficient locomotion concept is the other. This chapter will quickly describe some of the findings in literature about turtle locomotion. Generally, it is hard to clearly define the flipper trajectories of a sea-turtle. Video footage from turtles in free nature usually only give a few seconds of fin trajectories.

Extensive studies have been conducted by Davenport et al. [3]. They analyzed the locomotion of marine and freshwater turtles. Using these results, the general minimal and maximal angular limits of the fin-mechanism was defined. As it is described in [2] Figure 2 shows the maximal limits in each degree of freedom. The maximal limits of the trajectory range is one important guideline for designing a robotic

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implementation. Other studies on turtle fin locomotion were conducted by A R Rivera [4], Dinghui Chu [5] and Jian'an Xu [6].



Fig. 2. Trajectory ranges of a continuous forward swimming motion. Taken from [2] based on [3]

To sum up the biological studies on sea-turtle locomotion it should be noted that all data clearly points to fully actuated 3DOF flipper movement combined with a flipper torsion. Data from [3] give detailed insight in possible trajectory definitions. Especially the feathering motion or in-line motion of the fin is clearly visible. Pure fin inclination and flapping motion would therefore not sufficiently copy the turtles locomotion.

C. Robotics - State-of-the-Art

Having read about the biological facts on turtle locomotion one can now compare nature with already existing robots.

In [7] and [8], robots with small 1DOF flippers have been presented. These robots demonstrate how agile a robot can be with only small flippers and limited degrees of freedom. However, this propulsion mechanism is not very close to the natural antetype and also does not provide high speeds. Flapping fin models and measurements in [9] also show that elastic flippers are up to three times more efficient than rigid ones.

In comparison, the Aqua Penguin from Festo and Finnegan [10] are two robots presenting a 2DOF fin mechanism. The AquaPenguin is remarkable and again shows the high agility and freedom in motion that fin actuation brings along. Finnegan on the other hand is a large research robot developed at the MIT. It is over 2.5 m long and has four 2DOF flippers. This robot is one of the most advanced and demonstrates a vast set of maneuvers. Also the acceleration and change of direction is rather impressive given the size of the robot.

Interesting experiments have also been conducted with the 1DOF flapping fin concept of the AQUA robot [9]. The team around the Finnegan robot has made many studies on fin trajectories and the resulting thrust forces. But both robots are focused on 1DOF or 2DOF actuation. Theory and biology, however, clearly suggest that a 3DOF fin actuation would increase both thrust production as well as agility. Especially in [11], the authors demonstrate the effect of the, as they call it, *in-line motion* of the flipper. During the recovery phase (forward upward motion), the fin pitch minimizes the drag, during the power stroke (backward downward motion) the fin maximizes the thrust force generated. In our case,

the backward motion significantly adds to the thrust as the additional degree of freedom augments and optimizes the relative water flow around the fin and thus generates higher forces.

So far, no robot has been able to move the fin in 3DOF. Also the 2DOF mechanisms are based on a rather standard mechanical method. The motors used for each degree of freedom are housed in separate modules. This technique is still feasible for 2DOF but causes serious mechanical problems when a third dimension is added due to sealing and cabling. A serial solution also adds additional inertia due to the motors and modules weight that have to be moved together with the fin.

D. Research Objectives

The 3DOF fin mechanism is undoubtedly the main feature of the robot. As it was shown in the sections above, turtle locomotion is highly multidimensional and so far, no working hardware can fully examine this fact.

The overall goal of our project therefore was to design, implement and test a working robot able to perform fully 3DOF fin trajectories. As underwater robotics is dealing with an environment quite unfriendly to electronics and materials, the robot should be robust and designed in such a way that future missions can be undertaken without having to change the hardware. Sensors or other modules should be easily attachable to minimize mechanical changes as these increase the risk of leakage. The robot has therefore to be considered a platform rather than a single experiment.

III. HARDWARE DEVELOPMENTS

Underwater robots depend on a robust hardware. Unlike ground robots, underwater systems have to be carefully planned from the very beginning. The following sections describe the chosen solutions within Naro-tartaruga.



Fig. 3. Naro-tartaruga complete construction, without hydrodynamic shell.

The robot is based on a aluminium tube as center of the robot. This tube contains most of its electrical components. Mechanical parts were simplified as much as possible in order to optimize production times. The actuation unit, however, is by nature very complex. Here, the parts were kept as small and compact as possible, while minimizing complexity for production.

The robot was designed for long missions and deep dives. Similar industrial robots of the same size are commonly used in waters less than 100 meter depth. Most harbor and shore sites can be covered with such systems. Naro-tartaruga was designed mainly to operate in depths similar to the lake of Zurich (maximal depth: 136 m). The design of the main hull assumed a maximal water pressure of 15 bar. Strong foam blocks adjust the robots neutral buoyancy. However, no turtle-like shell is required for diving. Figures 3 and 4 shows the robot with and without turtle shell. This shell is only needed to optimize the drag forces as the robot glides through the water. If the shell is added, the mass of the whole robot augments not only by the mass of the shell itself but also by all the water "captured" within the shell, as this water also has to be accelerated with the robot. The robot then has a mass of approximately 182 kg.



Fig. 4. The main parts of the robot with the streamlined turtle shell.

Naro-tartaruga can be summed up as follows: A main tube contains the "organs" of the robot. Two symmetrical actuator units move the flippers in the front. A head and tail module contain more electrical components and are interchangeable quickly. Durable foam balances the mass and volume of the robot to adjust buoyancy. A shell, not waterproof, optimizes the water flow around the robot body, but is not mandatory for dives. More details about the hardware setup can be found in [12].

IV. SYSTEM MODELING

Simulation tools developed in MATLAB were used to simulate the robots behavior and the expected fin forces. These tools allow furthermore to search for optimal fin trajectories and to come up with a control structure proposal in order to control the robots motions. The simulation tools were split up in two components: the fin model and the overall system where the fin model gets plugged into.

As the mentioned literature describes, turtle locomotion is based on lift forces produced by the fin profile while moving through the water. To simulate the acting forces and torques generated by a moving fin, the fin model is based on small profile element models and assumes laminar flow conditions for which the standard lift and drag formulas are valid (more details in [12]). The fin is modeled as a standard NACA0015 profile with different chord lengths at the fin base and fin tip. Figure 5 shows a cross-section through one fin element and names the important parameters such as relative flow, finpitch angle, angle-of-attack, lift vector, drag vector and the resulting force. The gray line represents the fin trajectory.



Fig. 5. Cross-section and forces of a fin element based on a NACA0015 Profile. Based on the fin-element velocities and the incoming flow, the angle of attack and the resulting forces can be calculated.

V. ROBOT MODEL

As underwater locomotion in 6DOF is highly nonlinear and coupled, the control of such a system is very complex. A precise representation of the dynamics in a model is nearly impossible as water characteristics, turbulences and added mass effects are very complex to model and hard to validate. Complex multidimensional fluid dynamic simulations are necessary to get information on how the robot interacts with the water. But even with such simulations it is hard to validate the results. For this reason a simple approach is chosen, describing the robot dynamics via the classical Newton-Euler equation of motion. The overall robot model is based on [13].

To start modeling the motion of an underwater vehicle, three coordinate frames were defined: kinetic analysis of forces and their effect on the acceleration of the body are calculated in the body fixed frame K_B . Kinematic analysis of the speeds and position of the robot however are expressed in the water frame K_W . The earth frame K_E is only needed for graphical representation, as long as no water flow is modeled.

Position and orientation are expressed in the fixed frame K_W and are denoted by η . ν denotes the linear and angular velocities in the body fixed frame K_B and τ describes the forces and torques also in the body fixed frame. The dynamic and non linear model of the turtle is based on the following equation of motion (EOM):

$$M\dot{\nu} + C(\nu)\nu + D(\nu)\nu + g(\eta) = \tau$$

: $M = M_{RB} + M_A C(\nu) = C_{RB}(\nu) + C_A(\nu)$

with M_{RB} , M_A the inertia matrices (rigid body and added mass), $C_{RB}(\nu)$, $C_A(\nu)$ the matrices of Coriolis (rigid body and added mass), $D(\nu)$ the damping matrix, $g(\eta)$ the vector of gravitational forces and moments and τ the vector of control forces. The coriolis matrix and added mass matrix follow the method of [13] whereas the drag forces were estimated by approximating the robot as with cylinders. For each cylinder, lift and drag forces were estimated using the equations presented in [14].

Solving the EOM by $\dot{\nu}$, the robot accelerations, both linear and angular, can be calculated at each time step. Integrating

with

the accelerations and using the kinematic equations listed above, one can calculate the robots state in the fixed frame as a function of fin forces. See [12] for further details on the force computations.

VI. CONTROL STRATEGIES

Getting the robot to swim in a controlled manner is a big challenge. So far no swimming robot had a fully 3DOF fin actuation system. Furthermore, only little data is available about how other robots are being controlled.

A. System Challenges and Control Goals

For now, we are not interested in complicated maneuvers. Also hovering on the spot or diving maneuvers are more complicated than they may suggest. The first mode of operation that was controlled is the so called "flight-mode". In this mode the robot constantly swims forward. Only slight changes to its swimming direction are made in order to stabilize the robots heading. Like this, a human or automated high-level controller can direct the robot along desired vectors. Having a stable "flight-mode" will allow future implementations of "go from A to B" tasks, as long as they can be reached without tight turning maneuvers.

Limiting the space of possible motions to only a "flightmode" already reduces the complexity of the system. However, there is another factor that needs careful consideration.

Unlike, for instance, helicopters or wheeled robots, a flapping fin robot does not have a direct or even linear dependence between motor rotation speed and resulting thrust. A fin can flap continuously but only a slight change in the fin pitch motion, for instance, influences the resulting forward force entirely. It is thus the combination of all motions together, that defines the resulting forces on the robot. A robot with three individually driven and steerable caster wheels is a good analogy. Only a controlled combination of their speeds and direction will allow the system to move in the desired motion. In addition to the cross-coupling of the actuators, the system is also periodic. This rises the question whether the control should be continuous, periodic or averaged.

As the robot undergoes a periodic pitch motion during the up-down phases of the fin-trajectory, a continuous control of the instantaneous attitude and thrust generated by the fin would automatically try to minimize the undesired sideeffects such as a pitching motion. But since this motion is naturally unavoidable this control would inhibit the motion itself. The proposed control approach to solve this problem is thus to use a moving-average filter with the length of one fin-trajectory period on all states and assume a constant thrust vector for the fins. Basically, we assimilate the fins to propellers generating a constant thrust in a certain direction. This approach allows us to use a standard continuous PID controller that redirects the averaged thrust of the fins in such a way that the averaged rotations of the robot match the desired input.

B. Rate Control

As a first control approach, a continuous moving-average rate-controller was chosen to stabilize the robots roll, pitch and yaw rotation. Controlling the rotation rates will allow future hierarchical velocity and later even position control approaches. A rate controller also allows first trajectory optimization with the overall system where position control is of no importance but the rotational speeds should be close to zero.

Figure 6 shows roll, pitch and yaw rate control based on thrust vector control. Having the two front fins producing thrust slightly up or downward generates a torque around the y-axis, thus pitching the robot in the direction of the thrust. The tail fins can add to that torque similar to an airplane elevator. To produce a roll torque, the thrust vectors of the left and right fins point in opposite directions. Yaw control is achieved via different strength of the thrust vectors. By generating less thrust on the left than on the right side produces a yaw torque around the z-axis and lets the robot turn left and vice versa. The tail fins cannot add to any yaw control and are thus only needed for roll and pitch commands.



Fig. 6. Symmetric or asymmetric trajectory rotation results in either pitch or roll momentum. The tail fins can add torque. Yaw motion is induced with differing thrust vector magnitudes.

There are probably multiple solutions how the thrust can be redirected. One would certainly be to look at each instance of the fin trajectory and search for an ideal angle of attack that generates the desired thrust. Such a continuous and interperiod control however is based on a precise model that is capable of estimating the actual water flow. A simpler approach is chosen here. It is based on a rotation of the complete fin trajectory about the robots y-axis.

Similar solutions exist also for a change in thrust magnitude. If the fin trajectory is designed with minimal angle of attack values, very little thrust is produced. It would thus be possible to generate a drag minimized trajectory on one fin and a thrust optimized trajectory on the other fin. As the angle of attack is hard to know in the real system, as it depends on the actual water flow and velocity of the robot, this solution is not considered in the first place.

Instead, to reduce the thrust on one side without having to recalculate or continuously adapt the fin trajectory, the individual motion amplitudes get decreased by a common gain factor. With a gain factor of zero, the affected fin would not move at all anymore and thus only the opposite fin provides thrust.

C. Trajectory Morphing

The previously described flapping amplitude gain used to generate a yaw torque is a first example of our trajectory morphing. The overall idea for designing a rate controller is to not continuously control the actual trajectory but to use predefined look-up table trajectories that get morphed uniformly by the rate controller.

The trajectory morphing for the roll and pitch command is different. Here, the trajectory gets rotated entirely. Figure 7 shows the rotation of a look-up trajectory (black) to a rotated trajectory (blue). The thrust vector generated by the original trajectory (averaged over the whole period) produced a thrust solely in x-direction. The new, rotated trajectory however contains a component in z-direction and thus produces a torque around the y-axis of the robot (green). If both fins, left and right, rotate in the same direction, a pitch torque is generated. If they rotate in opposite direction, a roll torque results. Combining the trajectory morphing with the trajectory gain factor allows thus a complete roll, pitch and yaw rate controller to stabilize the robot about a desired swimming vector.



Fig. 7. Graphical representation of morphing a look-up trajectory (black) to a rotated-trajectory (blue) that generates an averaged thrust or with a component in the z-axis.

The proposed trajectory morphing reaches some limits. The mechanical limitation of only 60° feathering motion does not allow strong rotations of the trajectory. Saturation functions make sure that the new, rotated trajectory commands do not move the motors outside their mechanical limits. In reality, the feathering velocity command is simply kept to zero until the rotated trajectory is back within the mechanical limits. The restriction of the trajectory morphing is considered unimportant as long as the robot has to be stabilized on a desired vector that does not undergo strong changes. For maneuvers that require rapid turns, the trajectory-morphing will not allow a satisfying control.

VII. SIMULATION RESULTS

With the described trajectory-morphing in place, simulations were conducted with different set of trajectories. Figure 8 shows on the top the x, y and z coordinates of the robot's position during a simulation without active control. It can be seen that the robot deviates sideways and surfaces slowly as it surges forward toward positive x. With active control and the same fin trajectory, the robot however is now able to follow the x-axis with no major deviation. It is even able to compensate the slight positive buoyancy that pushes the robot to the surface.



Fig. 8. The plot shows the robot position for both the open-loop and the closed-loop case. Without active control (open-loop) the robot slowly drifts sideways and surfaces. In the closed-loop scenario the demand rates are set to zero. The robot swims forward without any y-deviation and only a very slight z-drift. The latter cannot be controlled with the rate controller as the robot does not rotate but translates in z direction due to a slight positive buoyancy.

Figure 9 shows the performance of the rate controller. The averaged robot states follow with a certain delay the desired rates. If however sudden changes in different rotations coincide, the cross-coupling and the inertia of the system leads to longer delays until the system stabilizes on the new demands. The trajectory morphing is thus a working control scheme for small changes during a flight mode but not efficient for sudden drastic changes.



Fig. 9. Performance plot of the rate controller for various reference steps on all three dimensions (roll, pitch and yaw).

VIII. TEST AND VALIDATION

After a successful first pressure test, the robot was placed in a swimming pool. The software of the robot was limited to a fixed fin trajectory. With a joystick, the user could control the frequency between 0 to 1 Hz as well as the tail fins acting as elevators. This first test was not meant to produce any numerical data such as speeds or control errors. It was rather meant to analyze the passive stability of the robot, to trim the buoyancy and to get some first experience on the robots behavior to a standard sine-wave motion.



Fig. 10. First pool test. Naro-tartaruga gets watered with the help of a crane system and swims freely for the first time.

In Figure 10 one can see the robot hooked onto the crane to and being put in the water before slowly swimming towards the deeper area.

The robot is slightly positively buoyant. The center of gravity is slightly behind the fins and seems to be very well aligned with the center of buoyancy as it is very easy to rotate the robot about all its axes. During first swim tests with very low flapping frequencies, it could be observed that the robot seems stable around the roll and pitch axis. Yaw however is unstable. This instability was expected. A tail fin could help to passively enhance the stability. However, with a working yaw controller on the front fins, this instability can be counteracted without major difficulties.

In a second test phase, the trajectory morphing approach for yaw control was tested. The user had manual control over the fins flapping amplitude and the tail fins position. In this condition, the operator was able to steer the robot in the pool without the need of a human swimming with the robot and controlling its swimming direction. This test supported the fin morphing control approach and already demonstrated a high agility, despite missing the implementation of the coupled roll and pitch trajectory morphing. Naro-tartaruga was even able to slightly pull a human being through the water. It can be assumed, that with further tuning and control of the attitude, the robot would very well capable to accelerate and pull a human being that lies passively on the robot shell.

Summarizing, the first swimming tests were highly positive and promises very interesting future tests. First attitude control implementations will result soon in a fully controllable robot. Additional fin trajectory tuning will then enhance the speed of the robot. These tests however should be undertaken in the lake, as the pool with 25 m length is already slightly too small.

Videos of the first test can be found on http://www. youtube.com/watch?v=pqy_NSHcGLs.

IX. CONCLUSIONS

This paper presented the design and implementation of a novel underwater robot using fin propulsion. The major contribution in the mechanical design are clearly functional 3DOF fin mechanism as well as the structural flexibility for the internal components. Pressure tests and swimming tests already showed the hardware capabilities and promise successful future dives.

The robot Naro-tartaruga is a very robust, easy-to-work-on underwater robot with a unique propulsion mechanism. The trajectories implemented for first mechanical tests already match very well the biological counterpart and the simulation and control framework is running and produces results that are highly motivating. Qualitative validation of the control scheme will be one of the first and important steps in future pool tests. For now, the first movements in the water were promising and even strong enough to slowly pull a human.

First fin-trajectory optimization suggest mostly symmetrical fin trajectories that produce thrust in both down-strokes and upstrokes. Biological studies however suggest, that the turtle tries to minimize its energy consumption during the upstroke, as the active muscles during this motion are weak. This difference between technical implementation and biological example is highly interesting and deserves future investigation.

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