BIOLOGICALLY INSPIRED
ROBOTICS GROUP (BIRG)

BoxyBot, the fish robot

Design and realization

EPFL - Semester Project

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Abstract

The world of fishes is extraordinary diversified: each fish has evolved to adapt efficiently to its environment. Despite that fact, fish propulsion systems isn't used in common applications. However some universities are studying the possibility to develop better and noiseless propulsion systems for autonomous underwater vehicles with fishlike locomotion.

The review of fish robots shows that cruising has been already studied with success but the autonomy is always restrained. Maneuvering has been less studied.

Amphibot II modules are used to build the fish robot: the most adapted swimming mode is labriform or ostraciiform because it don't required a good hydrodynamic profile.

The fish robot, named BoxyBot in reference to the Boxfish, is 0.25 m long and can swim up to 0.37 m/s, the minimal radius of turning observed is 0.13 m. The robot can dive, go forwards and backwards, swim on the side and do spins. Relations between forward speed, amplitude and frequency of fin's oscillations has been characterized.

Contents

1 Aim of the project **3**

2 State of the art **4**
2.1 Fishes' anatomy 4
2.2 Review of fish swimming modes 5
2.3 Review of fish robots 7

3 Some possible configurations **12**
3.1 Amphibot II modules 12
3.2 Carangiform mode 13
3.3 Ostraciiform/Labriform mode 13

4 Realization of BoxyBot **16**
4.1 Mechanical design 16
4.2 Electronical design 16
4.3 Software 18

5 Performances **21**
5.1 Forward speed 21
5.2 Turning 26
5.3 Other motions 28
5.4 Trajectories' follow 29

6 Future work **31**

7 Conclusion **32**

A Mechanical drawings **33**

B Software **34**
B.1 PIC's program 34
B.2 Matlab 35
B.3 RS232 interface 36

C Web sites of fish robots **37**

D Translation english-french of fishes' vocabulary **38**

E Electronical parts **39**
E.1 Control board Amphibot II - body module 39
E.2 Power board Amphibot II - body module 40
E.3 Power board Amphibot I - head module 41
E.4 Development board for PIC16f876A 42

F motor control register summary [15] **43**

Chapter 1

Aim of the project

The goal of this project is to realize an autonomous fish robot able to move itself in water in 3 dimensions. It is intended to use amphibot II modules developed at the BIRG[1].

The principal guide line is:

- Review of fish swimming modes
- Review of fish robots
- Study of different possibilities to build a fish robot with amphibot II modules
- Realization and characterization of fins: maneuverability and speed
- Trajectories' follow

[1] Biologically Inspired Robotics Group

Chapter 2

State of the art

2.1 Fishes' anatomy

Fishes have different fins but every fish doesn't always have each fin that is mentioned here (figure 2.1).

The fins could be classified between paired fins and median fins.

- **Paired fins**: pectoral and pelvic fins
- **Median fins**: anal, dorsal and caudal fins

The fins' rays could be spiny or soft:

- **Spiny rays**: not articulated, stiff. Fins with spiny rays are used for stabilization.
- **Soft rays**: articulated with little muscles at the base of the fin.

The number of rays is variable: between 3 to 10 rays.

Fins are used in different art according to the fish's morphology and life's type. For example, the morphology is different if the fish live in the see or in a reef.

They also have an air bladder that permit them to adjust its buoyancy. It consist of a pocket of gaz of variable volume.

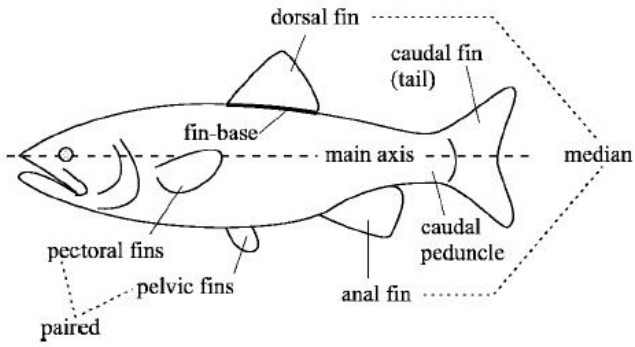


Figure 2.1: Terminology used to identifiy fins [10]

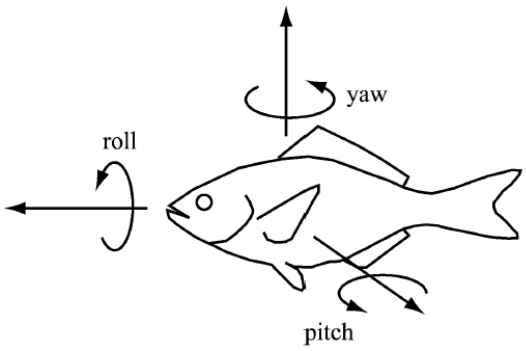


Figure 2.2: Referential of fish [10]

Figure 2.3: Glas eel

2.2 Review of fish swimming modes

The classification of fish swimming modes is done with Lindsey's classification [11, 1978]. That method classified from the body's part used to propelled (harsh area):

- Anguiliform: animals using that method couldn't really named fishes because their structure is very primitive. The entire body is used to propelled: a muscle wave is propagated perpendicularly to the body. It is very elongated, like snakes.

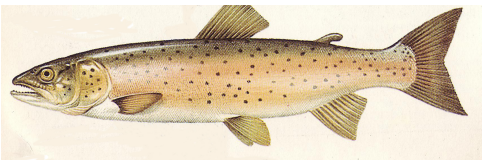
  Example: eel (figure 2.3).

- Subcarangiform is a term used to define fishes that are between anguiliform and carangiform. The oscillation is smaller than in anguiliform mode

  Example: salmon (figure 2.4, left)

- Carangiform: 1/3 of the last part of the body is used to propel fish by oscillating the caudal fin and the caudal peduncle (tail). A subclass of carangiform is thunniform. Thunniform fishes swim very fast. Their caudal fin has a high aspect ration. Their mainly type of locomotion is cruising.

  Example: tuna (figure 2.4,right). Small tuna can swim up to 60 km/h and the red tuna, the fastest fish in the world, up to 130 km/h.



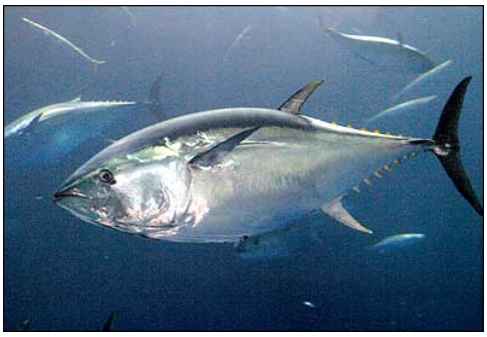


Figure 2.4: A danube's salmon *(left)* and a blue fin tuna *(right)*: they are cruising the most part of the time

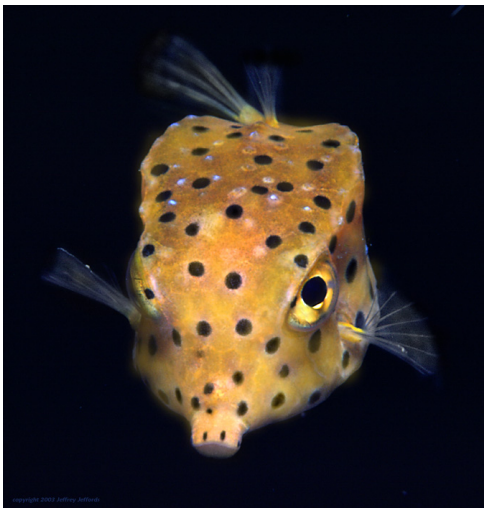


Figure 2.5: A blue gridled angelfish*(left)* and a yellow boxfish *(right)*: they maneuver the most part of the time

- Ostraciiform: only the fin's are oscillated and the rest of the body don't move. The paired fins are mainly used to propel. The caudal fin is less used. The bodies of these fishes are often inflexible cases. They mainly live in reefs. As they can only swim slow some of them have developed other art to protect themselves, like spit out poison. Their mainly type of locomotion is manoeuvring.

  Example: boxfish (figure 2.5, right)

- Labriform: alike ostraciiform fishes except that the caudal fin is used as a rudder and pectoral fins are used to propelled.

  Example: angelfish (figure 2.5, left)

2.3 Review of fish robots

A lot of institutes and universities has developed fish robots, that's why only the most important projects are exposed here. A summary can be found in tables 2.1 and 2.3. Pictures of these robots are in tables 2.2 and 2.4 . Web links can be found in appendix C.

- The *National Marine Research Institute* in Japan is working on multiple projects, including maneuvering, swimming performance and modular robotics for water. Their PF series is described in the table below. Another series of model robot have been built, called PPF-series, to explore the best power source for fish robots.

- The *University of Essex* in England work also on multiple interesting fish robot projects.

- The *Massachusets Institute of Technology* had worked on thunniform robot projects called *RoboTuna I* and *II*, their aim to develop a more efficient and less noisy propulsion system for underwater vehicles. Theses robots were not autonomous, their were attached to a tank contrary to their Robot Pike and B1 robot. B1 propelled itself with two frog's muscles in a glucose solution.

- The *McGill and York Universities* have transformed their Rex six legged walking robot in an amphibian robot that can also swim with a sort of six oars: the *Aqua project*.

- *Mitsubishi Heavy Industries* had developed a fossil fish robot in 2001. The purpose was to show a disappeared fish, called *Coelacanth*, to the visitors in amusements parks. The project is over for commercial reasons.

- The *Beijing University* in China has built a semi autonomous underwater vehicle propelled by a fin for archaeological exploration. The performances are remarkable, however it looks like more a torpedo than a fish.

- The *University of California* has recently build a biomimetic micro underwater vehicle with oscillating fin propulsion. Its length is only 12 mm and its weight is 1 g.

- Some robotic's club have also build fish robots but they don't reach the same performances. An example is *Dongle*, a fish robot developed by the *Seattle Robotic Society*.

Project	brief description	dof[a]	year
RoboTuna I *(or Charlie I)* and RoboTuna II, MIT[b] (USA)	*Thunniform fishes* designed to develop better propulsion system for autonomous underwater vehicles. Speed optimization, not autonomous, test attached in a tank.	8 joints around yaw	1995/ 2000
Robot Pike, MIT	Designed to learn more about the fluid mechanics that fish use to propel themselves in the goal to propel small autonomous vehicles via fish-like swimming to reduce energy consumption. Very quick turning and fast acceleration from a stop.	3 joints around yaw	1994
Robot B1, MIT	Use real frog's muscles for propulsion in a glucose's solution Length: ≈ 0.15 m	2 muscles to provide 1 joint around yaw	2001
PF200, NMRI[c] (Japan)	Designed to investigate the up-down motion of a small fish robot: ≈ 35 cm deep in 15 s Length: ≈ 0.3 m	1 joint around yaw and an orientable weight around pitch	-
PF300, NMRI	*Sea bream fish* designed for high turn-performance, operated by radio control Length: 0.34 m, maxi speed: 0.2 m/s quick turn : $\oslash$75 mm in 10 s at an oscillation of 2.2 Hz	2 joints around yaw	1999
PF550, NMRI	Designed for up-down motion. The caudal fin, consisted of 2 joints around yaw axis and can be oriented around pitch axis Length: ≈ 0.6 m	3 motors providing 2 joints around yaw and 2 around pitch	2003
PF600, NMRI	*Thunniform fish* design for study basic propulsion performance, operated by radio control Length: 0.6 m, speed : 0.1-0.4 m/s at an oscillating frequencies of 1-4 Hz	3 joints around yaw moved by 2 motors	1998-2000
PF700, NMRI	Designed to get high speed swimming, operated by radio control Length: 0.7 m, max speed : 0.7 m/s at an oscillating frequencies of 12 Hz	3 joints around yaw	2000
UPF2001, NMRI	Designed for high performances and multi-purpose-used Length: ≈ 1 m, maximal speed : 0.97 m/s	1 joint orientable around yaw or pitch	2001-2002

Table 2.1: Brief description of most interesting fish robots (first part)

[a]see referential in figure 2.2
[b]Massachusets Institute of Technology
[c]National Marine Research Institut

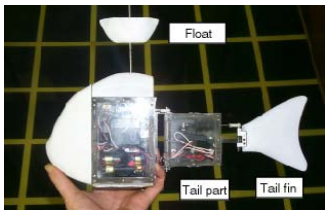
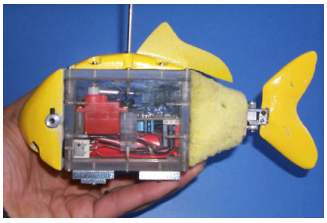
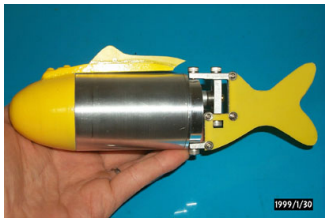
Charlie I	RoboTunaII	Robot Pike
B1	PF-200	 PF-300
PF-550	PF-600	PF-700
UPF-2001	 PPF-04	 PPF-05

Table 2.2: Pictures of the different existing fish robots (first part)

Project	brief description	dof	year
G1, G2, G3, G4, G5 and MT1, University of Essex (UK)	Different autonomous fish robots that swims like real-fishes and navigates by themselves	-	2003-2005
Aqua, McGill and York University	Amphibious robot developed from the Rex six legged walking robot	6 joints around the pitch axis	2004
Coelacanth fish, MHI[a]	*Fossil fish* for amusement parks and aquariums. Controlled by an external PC. Project given up for commercial reasons. Length: 0.7 m, weight : 12 kg	not communicate but a lot of joints and fins	2001
SPC-II, BUAA[b] and SIA[c] (Chine)	Semi-autonomous underwater vehicle for archaeological exploration Length: 1.23 m, max speed : 1.5 m/s	2 joints around yaw, perhaps between 0 and 2 around pitch	2004
Dongle, SRS[d]	Designed for amusement. Autonomous Length: 0.6 m, speed : $\approx$ 0.06 m/s, weight: 2.3 kg	2 joints around yaw	-
BASS-II, N. Kato (Japan)[6]	Rendezvous and docking with an underwater post in water current. Use of 2 pectoral fins to stabilize the robot.	2 pectoral fins: joints around yaw axis	2000
Boxfish, University of California [1]	micro vehicle controlled by PZT bimorph actuators Length: 12 mm weight: 1 g	2 joints around roll and 1 joint around yaw	April 2005

Table 2.3: Brief description of most interesting fish robots (second part)

[a]Mitsubishi Heavy Industries, Ltd.
[b]Beijing University of Aeronautics and Astronautics
[c]Shenyang Institute of Automation of the Chinese Academy of Science (CAS)
[d]Seattle Robotics Society

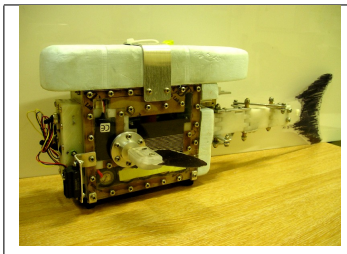
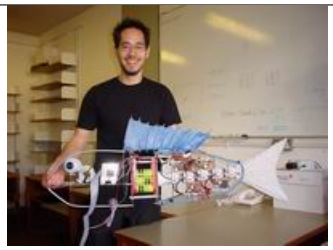
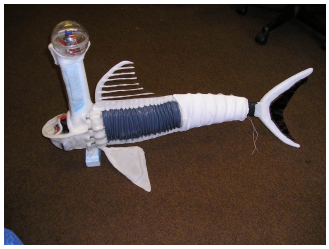
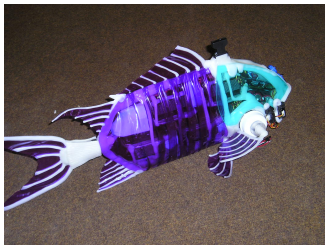
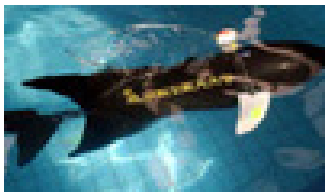
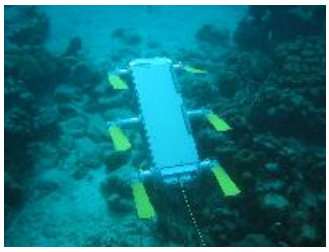
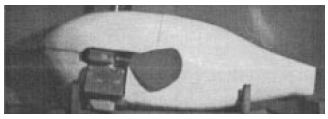
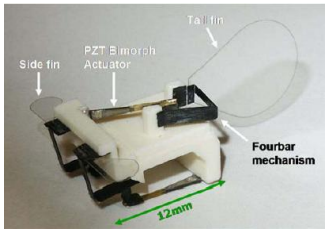
		
MT1	G1	G2
		
G3	G4	G5
		
Coelacanth	dongle	SPC-II
		
Aqua	BASS-II	Boxfish robot

Table 2.4: Pictures of the different existing fish robots (second part)

Chapter 3

Some possible configurations

3.1 Amphibot II modules

The amphibot II modules were designed at the BIRG in 2005, the first modules were available in may 2005. The principle is that each module is power supply and mechanically independent from another and can be easily replaced in case of damage. The modules' density is near water's density. Their is two type of modules: head and body modules.

The body module contains one motor. The head module contains two motors that are perpendicular to the body's motor. They communicate with I2C protocol. The motor control module was developed at the ASL[1] (appendix F).

For that project it was intended to use these modules and explore the different possibilities to build a fish robot with minimal modifications to modules. The challenge is to demonstrate the modularity and the capacity to work in water.

[1] Autonomous System Lab - EPFL

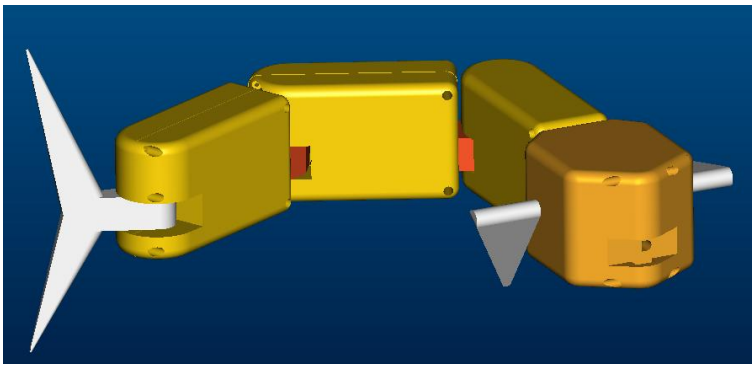


Figure 3.1: Fish robot designed for carangiform swimming mode with 3 body modules and 1 head module

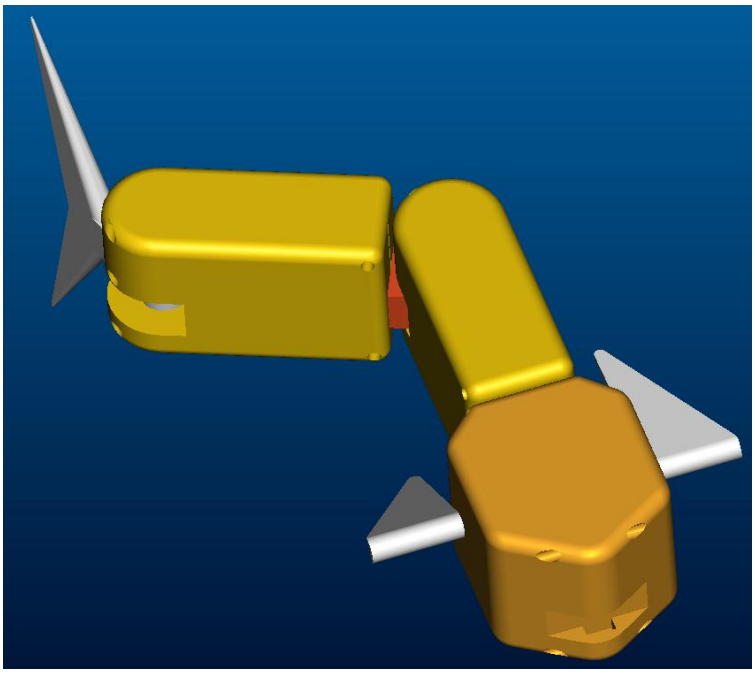


Figure 3.2: Fish robot designed for carangiform swimming mode with 2 body modules and 1 head module

3.2 Carangiform mode

A robot propelled by carangiform mode could be realized with two or three body modules and one head module. The caudal fin and peduncle, build with body modules, could be used to propelled the robot (figures 3.1 and 3.2). Head motors could be used to implement pectoral fins and used as rudders.

Carangiform fishes swim very fast and so hydrodynamic profile is very important. But it would be preferable not to modify the external mechanical design of amphibot II modules. The second limitation is that a lot of joints is required in the tail if we really want to mimic that mode. Moreover most of previous works on fish robots has explored that possibility and build efficient thunniform robots. That's the reasons why that possibility wasn't implemented.

3.3 Ostraciiform/Labriform mode

Fishes that uses ostraciiform or labriform modes have often inflexible cases for body and so it is very similar to the structure of amphibot II modules. With one head module and one body module it would be possible to maximize maneuverability and propulsion with pectoral fins. The caudal fin activated by the body module could be used as a rudder like in labriform mode or hybrid propulsion could be explored like in ostraciiform mode.

The Boxfish is a great example of ostraciiform propulsion mode, however it uses also their anal and dorsal fins to move. The second limitation of an ostraciiform robot will be the fact

Figure 3.3: Fish robot designed for ostraciiform or labriform swimming mode

that pectoral fins have only each one degree of freedom in place of five to ten per pectoral fins for the Boxfish.

Chapter 4

Realization of BoxyBot

The fish robot realized is inspired by the BoxFish and so were baptized BoxyBot. It use only two modules: one head and one body module. The configuration of BoxyBot is visible in figure 4.1

4.1 Mechanical design

Fins Fins are made of plate of polymer (PE or rubber). They are fixed to the modules with intermediate parts to provide easy change of the fins: fins are maintained with two pins. Remark that the attachement part for caudal fin is the same part as the original attach of amphibot II modules with little modifications after injection, the same mould can so be used. Fins can be made with different thickness up to 4 mm. If the groove is larger than necessary an additional part is put. See appendix A for mechanical drawings.

fins realized	aspect ration	surface [cm^2]
caudal fin	2.9	35
small pectoral fins	0.6	25 x 2 fins
big pectoral fins	0.6	50 x 2 fins

The two caudal fins and the four paired of pectoral fins realized are visible in figure 4.2. The dimensions are in table above. Fins made of rubber will be named "flexible" in the rest of the report.

Buoyancy The final density is bigger than water's density so it sinks. The robot is also not enough vertically distribute. So a mass is added under the body and a float (expansed PS) above.

Final robot's length is 25 [cm] with the caudal fin.

4.2 Electronical design

Control Previously, amphibot I modules were controlled by an outside computer. The modules were connected with a cable and were only power autonomous. In goal to prevent influence of the cable to the dynamic of the future fish robot a PIC16f876A is added on the electronic board of the body module (appendix E.1). It is used as the master for I2C communication.

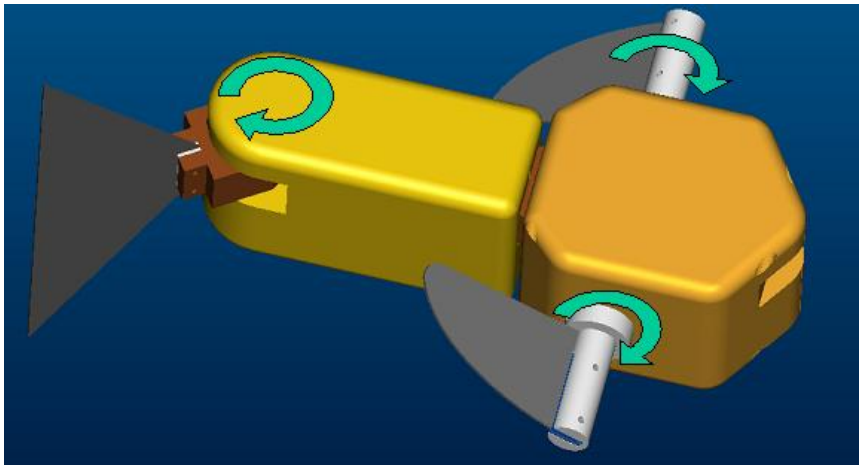


Figure 4.1: Assembly of BoxyBot. Green arrows show the active joints.

Figure 4.2: Different fins. Left: caudal fin. Right: pectoral fins.

Magnetic contact To stop power supply from batteries without opening the module, a magnetic contact is added in the power board of the body module (appendix E.2). However, the module have to be opened to program the PIC and to recharge batteries.

Because the electronic board of the head module were not available, the electronic board of Amphibot I is used for the head. To keep the possibility to stop power supply, little modifications were made on that board (appendix E.3).

4.3 Software

The PIC is programmed in language C with CCS compiler and an In Circuit Debugger (ICD) from microchip [12]. Motors are controlled in position without specific profile of velocity, the signal compute by the program is a sinusoidal signal, a lookup table is used to compute that sine and time is incremented in an interrupt.

Series of motions Because of the fact that the robot have to be dry, open and reprogrammed each time that we want to test another program, it is possible to enter a table of amplitude, frequency, phase, offset and sequences duration for testing a series of motions.

The flow charts of the program are visible in figures 4.3 to 4.6.

Development and graphical visualization An external board can be used to test the program (appendix E.4). That board have the same PIC that will be the master and replace the PIC in the fish. When using that external board it is important to be sure that the controller in the fish don't act as a master. So it is recommended to erase it while using the external board.

When using the external board, it is possible to define a constant *(GRAPH)* in the header file to visualize the movement of the fins. The values of the positions of the three fins will be sent by RS232 communication. A program on the pc will take the values and write them in a text file, easily usable with Matlab. The pc software is in appendix B.3 and matlab code in B.2.

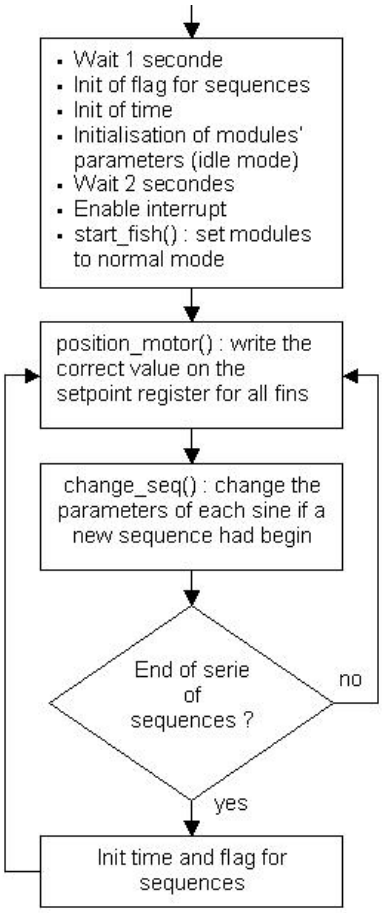


Figure 4.3: Flow chart of the main programme

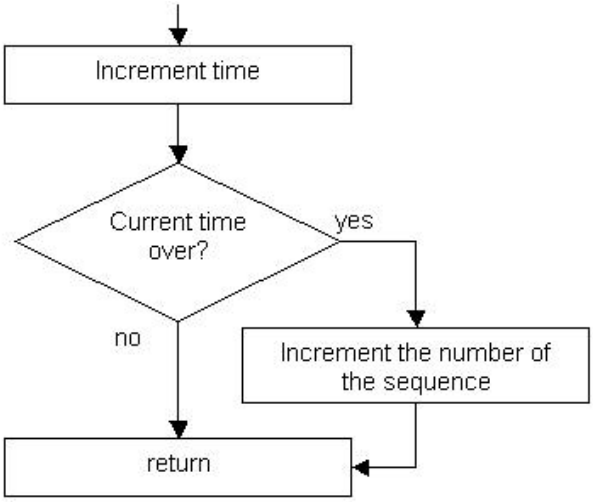


Figure 4.4: Flow chart of the interrupt function

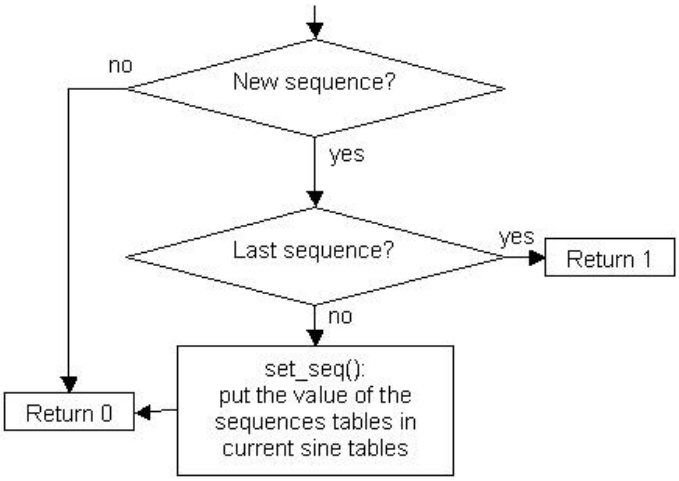


Figure 4.5: Flow chart of check_seq()

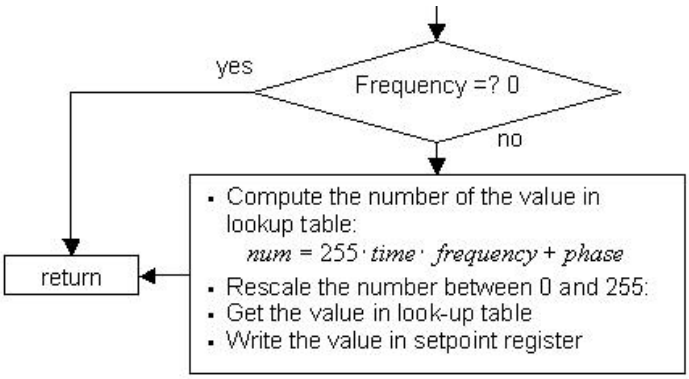


Figure 4.6: Flow chart of position_motor()

Chapter 5

Performances

The robot has no sensors and so it is very difficult to control its trajectory. Explore the maneuverability is possible but characterize isn't without any feedback. Speed of the robot is characterized and turning is measured very approximately. Some other motions were explored like diving, do spin or move backwards.

5.1 Forward speed

Speed is a function of amplitude and frequency of the fins' oscillations. It depends also on a lot of parameters like aspect ratio, stiffness or surface of the fins.

Forward motion There are three configurations that make move the robot forwards (figure 5.1):

- Propelled by caudal fin (A)
- Propelled by pectoral fins (B)
- Propelled by caudal and pectoral fins (C)

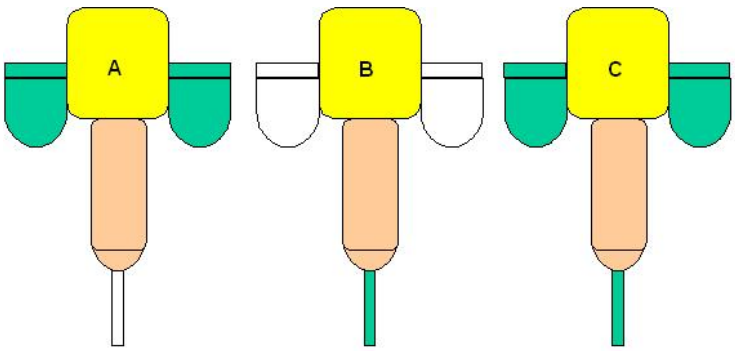


Figure 5.1: Possibilities to obtain forward motion. View from above. Green parts are active and white parts are passive.

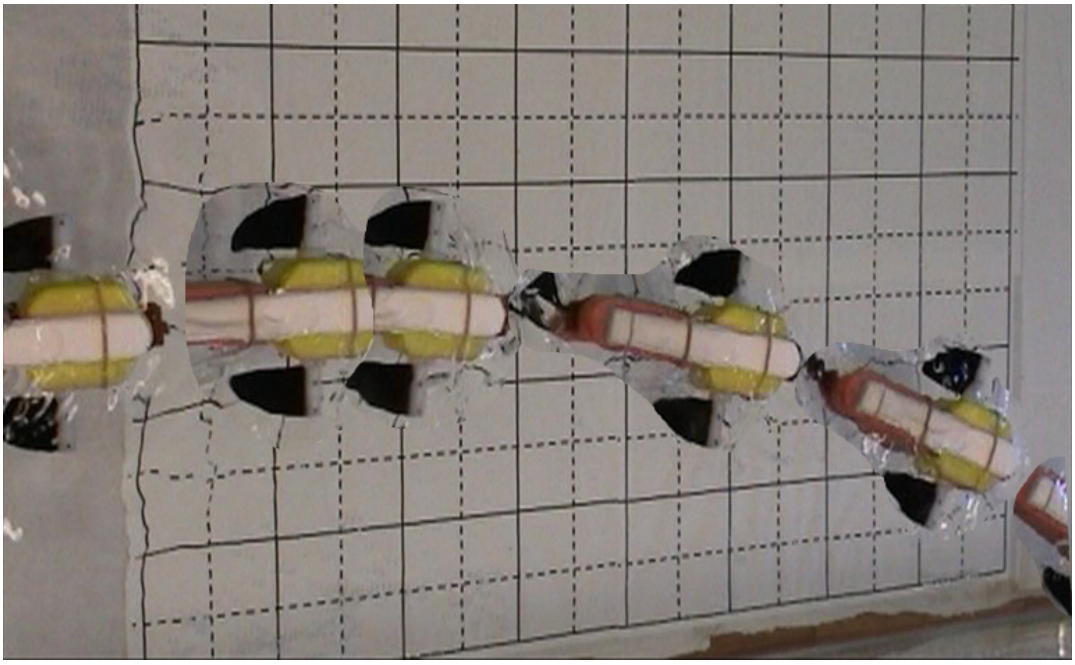


Figure 5.2: Sequences of typical forward motion with pectoral and caudal fins

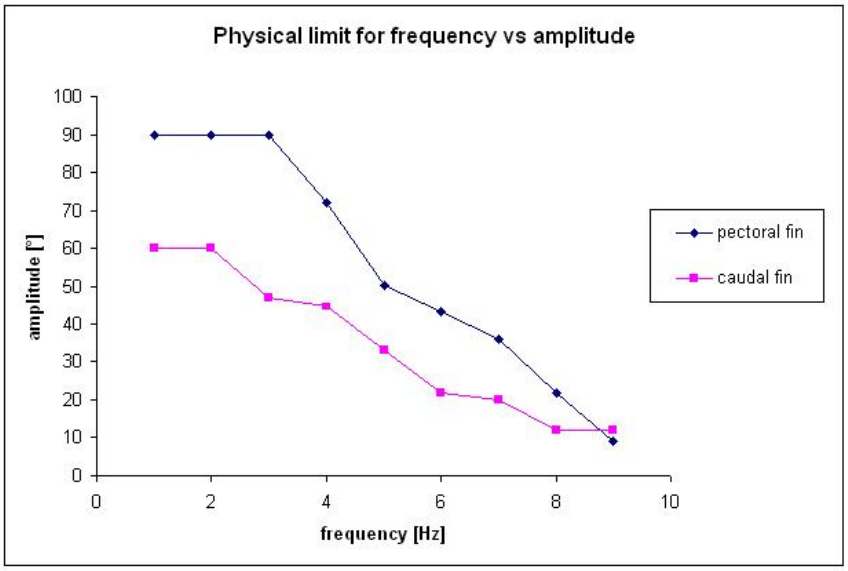


Figure 5.3: Physical limit of motors

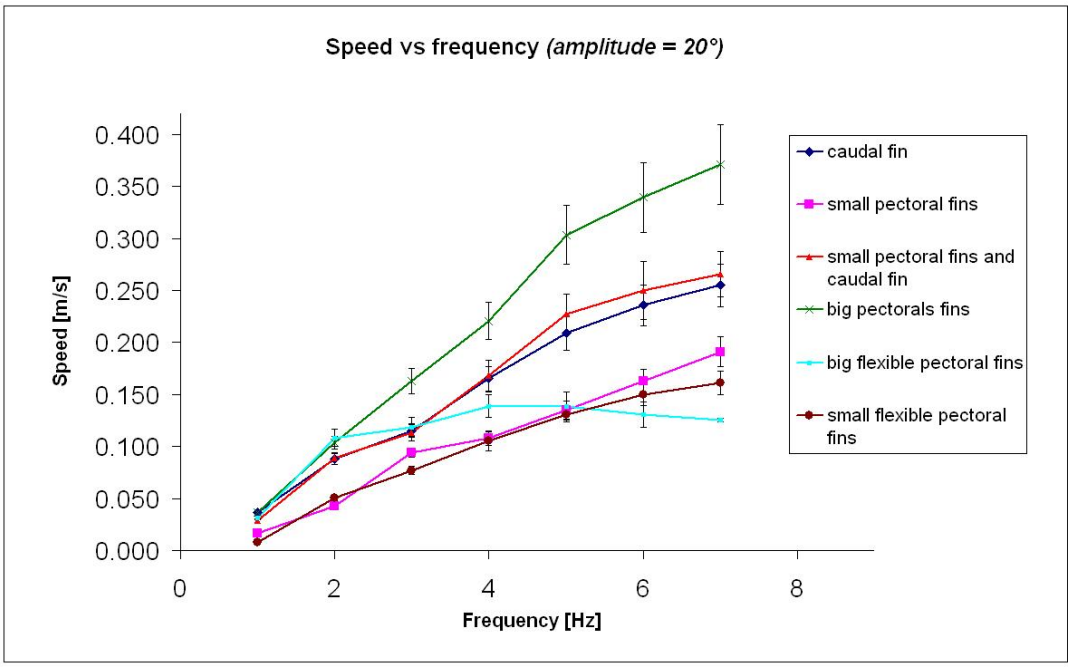


Figure 5.4: Speed vs frequency of fins' oscillation for a fixed amplitude at 20 °

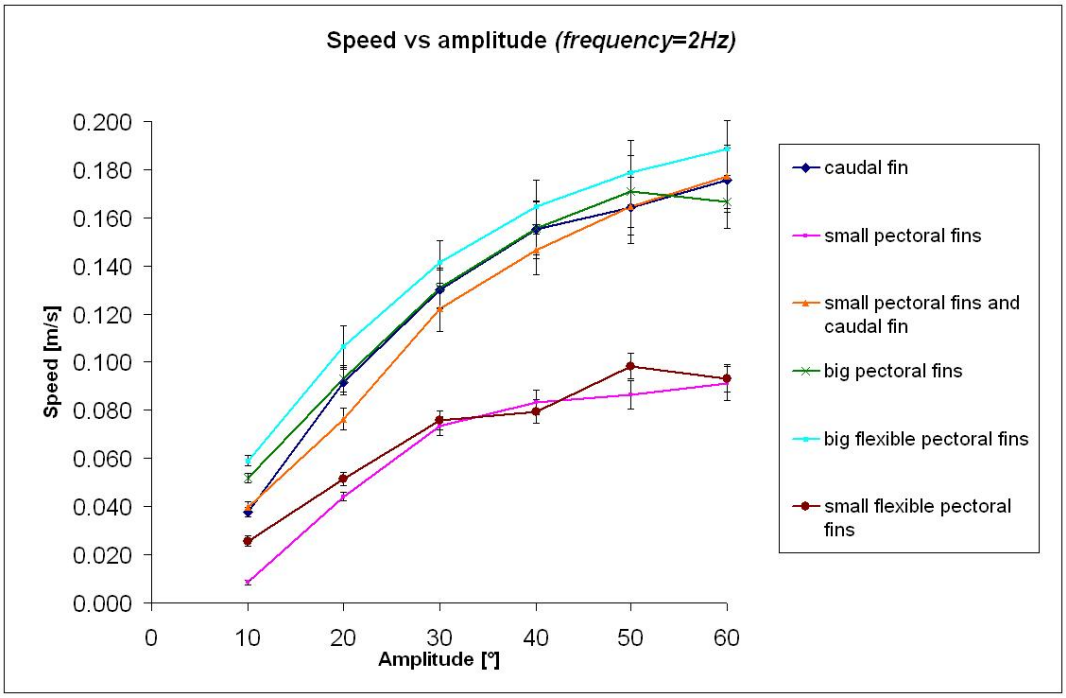


Figure 5.5: Speed vs amplitude of fins' oscillation for a fixed frequency at 2 Hz

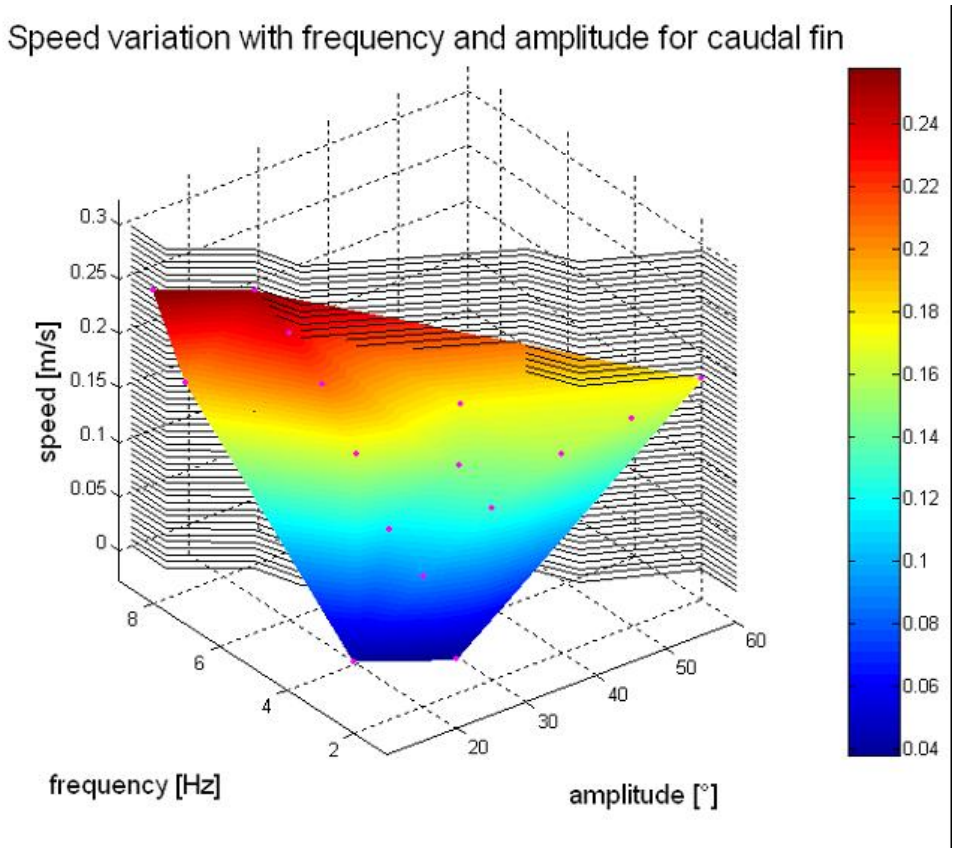


Figure 5.6: Approximated surface of speed vs frequency and amplitude for the caudal fin. Pink points correspond to measure points. Red color correspond to high speed and blue color to low speed. Black lines shows the physical limit. The surface can be used to chose amplitude and frequency for a desired speed.

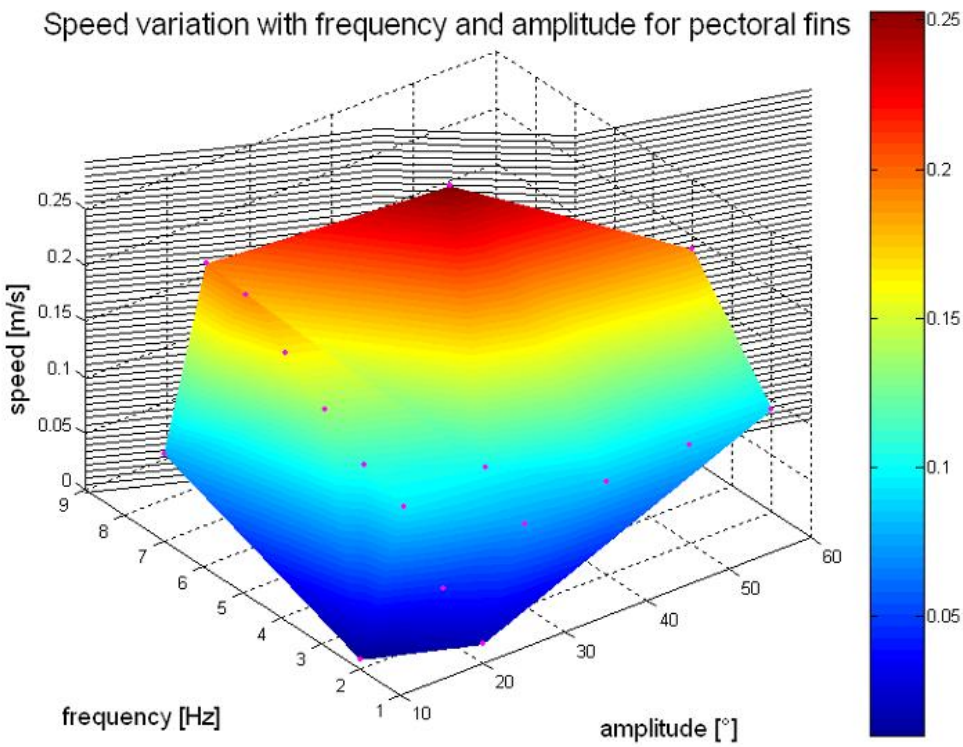


Figure 5.7: Approximated surface of speed vs frequency and amplitude for the pectoral fins. Pink points correspond to measure points. Red color correspond to high speed and blue color to low speed. Black lines shows the physical limit. The surface can be used to chose amplitude and frequency for a desired speed.

Measure of the speed As explained before, the robot never goes straight. So it is necessary to measure distance in two directions. The curve traveled is then approximated to a line. In that goal, a video camera is used to film the robot from above. A squared paper is placed under the aquarium to provide the possibility to measure distance. The accuracy of measure is then about ± 2 [cm] in both directions and ± 0.08[s] for the time (video accuracy). That method provide an accuracy less than ± 0.02 [m/s]. A typical measure's sequence is shown in figure 5.2.

Physical limit The physical limit of the motors, visible in figure 5.3 is determined without charge (out of the water). It is defined by the maximal values of sine parameters that the motor can follow without diminution of amplitude. The software limit is above the physical limit.

Results The results obtained are visible in figures 5.4 to 5.7.

- Speed is proportional to frequency
- Speed is proportional to amplitude. We see a saturation that arrived near $90\,^{\circ}$ because at that amplitude the motion is opposed to the direction of desired motion
- Use of the caudal fin get more speed than with small pectoral fins. We can also see that using pectoral and caudal fins together in place of caudal fin only don't provide a better speed
- A too weak stiffness isn't appropriate for frequencies above 2 [Hz] but can be better for smaller frequencies.
- Speed is highly proportional to fins' surface

5.2 Turning

The possibilities for turning are multiple (figure 5.9). There is two main phenomena that make the robot turn:

- Caudal's offset shift the centre of gravity and the fins' forces cause moments
- Hydrodynamic forces on the caudal fin

For small speed the second phenomena is negligible. In the case of the configurations C and D at high speed, the left pectoral fin increase water's velocity and hydrodynamic forces are important on the caudal fin.

The measure of radius of turning isn't very accurate because the motion of the robot cause waves that perturb it. Because of that, the curve wasn't really a circle.

Results Radius of turning is independent of rotational speed. Each configuration prensented in figure 5.9 have been tested and works.

- configuration A : the relation between caudal offset and radius of turning is shown in figure 5.10. The minimal radius obtained is about 20 cm. The maximal value that could be measured is about 60 cm because of the dimension of the aquarium.

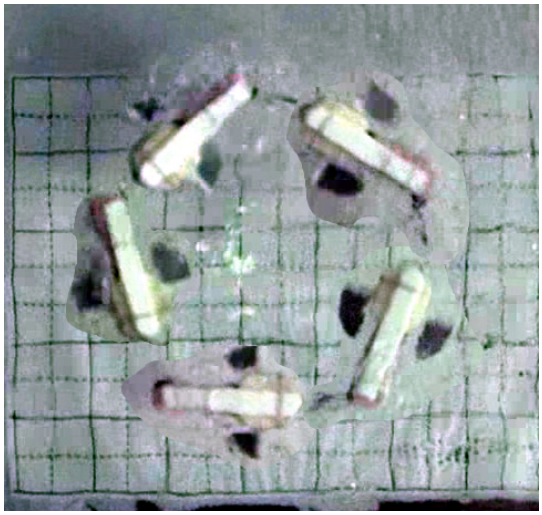


Figure 5.8: Sequences of typical turning with configuration A. Paper is 5 cm squared.

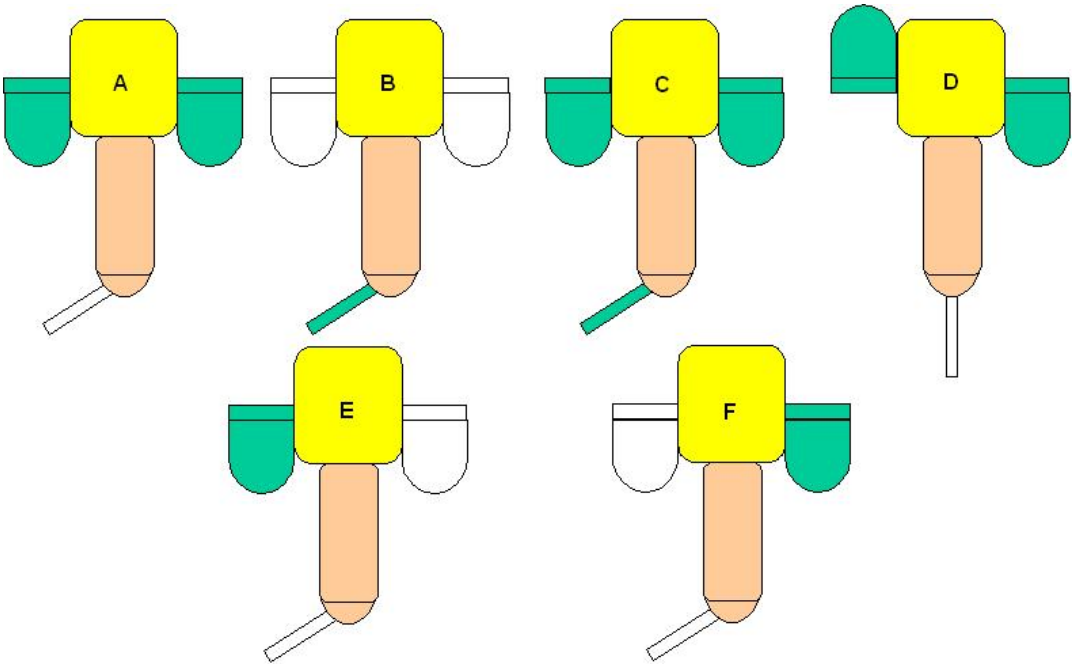


Figure 5.9: Different possibilities to turn left. View from above. Green parts are active and white parts are passiv

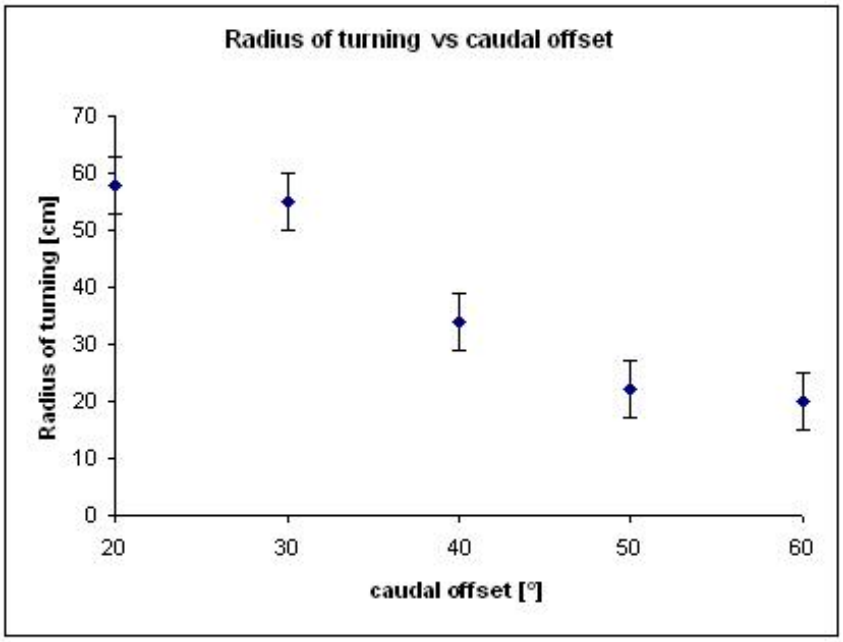


Figure 5.10: Radius of turning vs caudal offset obtained with A configuration of figure 5.9

- configurations B and C : in these cases the mean offset of caudal fin is smaller than in A and so the radius of turning couldn't be smaller. However with that possibility the speed of turning can be higher.
- configuration D: a radius of 13 cm has been observed but it wasn't more explored
- configuration E: it works only if the caudal offset is sufficient to shift the center of gravity further than the left pectoral fin.

5.3 Other motions

Spin The robot can spin with an offset of the left pectoral fin equal to $\pm 90\,°$ and the right pectoral fin opposed. With the big pectoral fins, the moment is sufficient to move the robot around the roll axis. With the small pectoral fins or in moving slower the big fins it is possible to keep on one side. From that position if the caudal fin is moved the robot can go forwards in propelling alike dolphins.

Move backwards The robot can move backwards: the pectoral fins' offsets are set to $180\,°$. However a little offset of the caudal fin deviate the water flux and the trajectory is very instable. Indeed it is an instable equilibrium point contrary to forward motion where the equilibrium point is a stable point. Because of that, robot can't go as fast as in forward motion if we want that the trajectory remain controllable.

Diving Capacity of diving motion has been demonstrated but couldn't be more explored. Indeed the aquarium used is only 22 cm deep and the amphibot modules are build to sustained 25 cm of water without leakage but the modules haven't been tested.

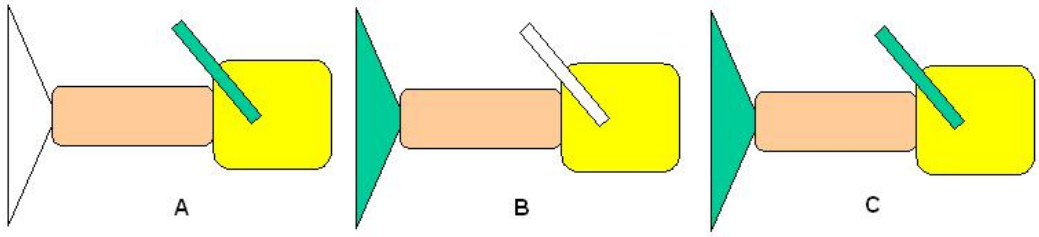


Figure 5.11: Different possibilities to dive. View from side. Green parts are active and white parts are passive

Walking If the pectoral fins are moved synchronously, the robot can go forward, dragging on the floor. Pectoral fins lift the robot and it fall further. However there is multiple drawbacks:

- works only with enough stiff fins (not with flexible fins)
- the friction coefficient has to be high: PE pectoral fins on smooth surface isn't appropriate
- at each step the robot fall, the chock could damage the robot

5.4 Trajectories' follow

Except motor's encoders, the robot has no sensors so it is impossible to follow a trajectory. However it is possible to chose a series of motion and to specify how long we want that the robot execute it. The motions are then executed in loop. An example of command is visible in figure 5.12.

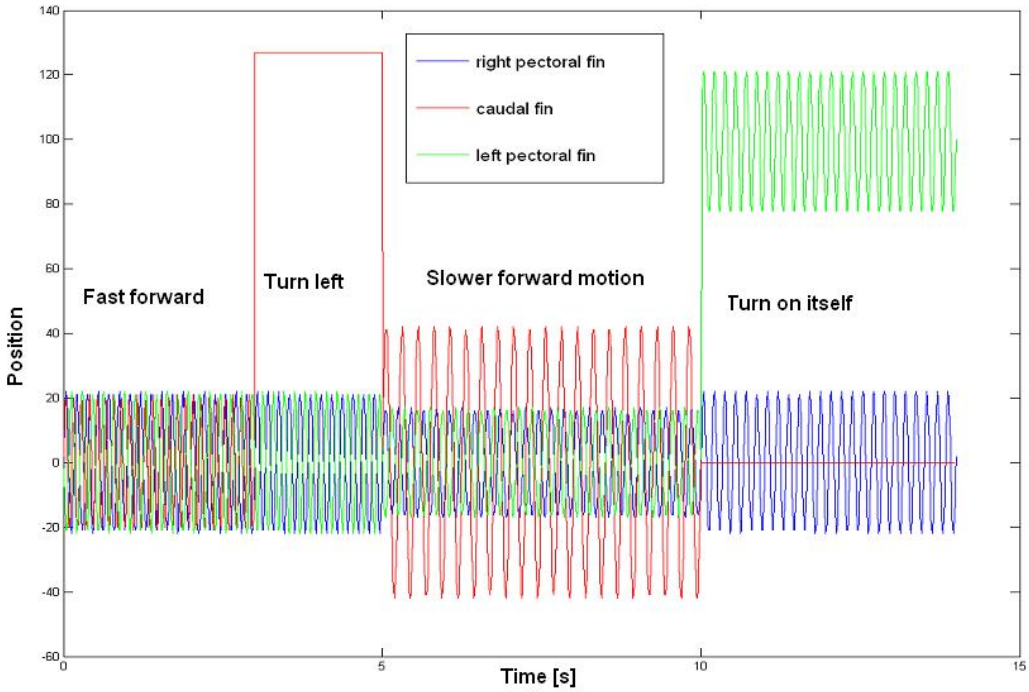


Figure 5.12: Example of a series of motions that can be easily generated from the PIC

Chapter 6

Future work

The next step is to add sensors, however it would be interesting to search for the better aspect ratio of pectoral fins. A point that have to be improve is the method to program and recharge batteries: opening the module very often cause a lot of mechanical problems and take a lot of time.

The future possible works could be resume in the points below:

- Characterization of diving
- Characterization of fins for different aspect ratio
- Adding the possibility to get out cables for recharging batteries and program without open the all module
- Adding of proprioceptive sensors : tilt sensor on roll axis
- Adding of exterioceptive sensors : light sensor

Chapter 7

Conclusion

The fish robot realized is 0.25 m long and can swim up to 0.37 m/s, the minimal radius of turning observed is 0.13 m. The robot can dive, go forwards and backwards, swim on the side and do spins.

The speed is proportional to frequency and amplitude of the fins' oscillations and is highly proportional to the surface of the fins. Rubber fins provides smaller speed than PE fins and above 2 Hz they aren't appropriate for propulsion.

The caudal fin provide a bigger speed than the small pectoral fins but has a bigger surface. Use of the big pectoral fins provide the best performances. But like the development of fishes in the nature, we have to adapt the robot to its environment: a smaller speed is much appropriate in a confine space. So the use of the small pectoral fins could be better for testing maneuvers in that aquarium in the future.

Appendix A

Mechanical drawings

Appendix B

Software

B.1 PIC's program

B.2 Matlab

B.3 RS232 interface

Appendix C

Web sites of fish robots

These web sites were visited in march 2005.

- RoboTuna I, http://web.mit.edu/towtank/www/Tuna/Tuna1/tuna1.html
- RoboTuna II, http://web.mit.edu/towtank/www/Tuna/tuna.html
- RoboPike, http://web.mit.edu/towtank/www/Pike/pike.html
- SPC-II,http://www.vieartificielle.com/nouvelle/?id_nouvelle=769
- Dongle,http://www.seattlerobotics.org/encoder /200211/autonomous_robotic_fish.html
- B1, http://www-personal.umich.edu/ bobden/biomechatronic _devices.html#Movie%20of%20our%20Biomechatronic%20Fish
- NMRI's robots, http://www.nmri.go.jp/eng/khirata/fish/index_e.html
- Essex University's robots, http://privatewww.essex.ac.uk / jliua
- Coelacanth fish, http://www.mhi.co.jp/enews/e_0898.html
- Aqua project, http://www.aquarobot.net:8080/AQUA/AQUA/index_html

Appendix D

Translation english-french of fishes' vocabulary

English		French
Trout	=	truite
Tuna	=	thon
Salmon	=	saumon
Swordfish	=	espadon
Mackerel	=	maquereau
Herring	=	hareng
Pike	=	brochet
Carp	=	carpe
Cord	=	morue
Boxfish	=	poisson coffre
Angelfish	=	poisson ange
eel	=	anguille
lamprey	=	lamproie
buoyancy	=	flottabilité
air bladder	=	vessie natatoire
fin	=	nageoire
caudal fin	=	nageoire caudale
pectoral fins	=	nageoires pectorales
pelvic fins	=	nageoires pelviennes ou ventrales
median fins	=	nageoires impaires
spiny rays	=	rayons pineux
soft rays	=	rayons mous

Appendix E

Electronical parts

E.1 Control board Amphibot II - body module

E.2 Power board Amphibot II - body module

E.3 Power board Amphibot I - head module

E.4 Development board for PIC16f876A

Appendix F

motor control register summary [15]

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