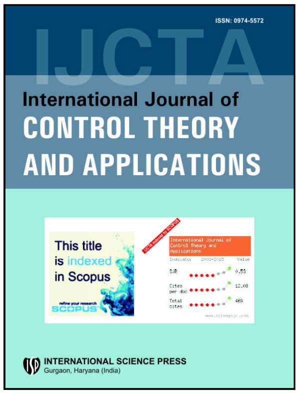

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A Survey on Motion Control of Robotic Fish

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Abstract: This paper is a survey based on motion control of robotic fish using different approaches for modelling, design, vision, speed and control. Many researchers find the fish efficiency and their maneuverability such as to find its speed and pike of its acceleration and eel for its threading everywhere. These robot fish are already being used in the fields like oceanographical observation, leak of the detection on pipe lines, search for mines and also underwater archeological exploration. To improve the performance of the fish we are following their approach for design, modelling and for controlling it using FPGA.

Keywords: Design, Speed,Self-control, Motion control, FPGA

1. INTRODUCTION

Fish has an astonishing properties of swimming and has inspired many researchers to develop a new type of autonomous under water vehicles. For this Robotic Fish vehicles are mostly preferred. For its design we are mainly considering mainly 4 parameters. The parameters in which survey is being done are Design, Motion control, Speed, Vision Based Self Control. Qi yuan Ren et al. proposed the model of approach for the motion control using different mechanical techniques in design and modelling [3]-[6] .Yonghui Hu et al. Proposed about how the parts of the fish should be like Speed, under water path planning by using image processing [7]-[9]. To sense the conditions under the water. WeiWang et al. proposed model forself-control using vision based technology to sensedata [10]. Section II describes about design and modelling.Section III describes about design and motion controlling. In Section IV, we turn our attention to the speed that increases performance power. In Section V, we explore about vision-based self -control of robotic Fish. Finally, in section VI, we conclude the survey by explaining each and every section.

2. DESIGN AND MODELLING

Qinyuan Ren et al. proposed pectoral fins mechanisms for accomplishing maneuvering, propulsion to robotic fish [11], [12]. Dynamic model will be best owed to a robotic fish that moved eventually. Tom's perusing pectoral fins incorporating flexible joints, wherever pectoral fin system will be molded by 2 inflexible segments joined for an attempt of torsional spring for furthermore damper [15], [16]. This sort of style prompts a web push for consistent recuperation and energy stroke speed around each fin beat. [14], [17].

2.1. Passive joint design and prototyping-

This style allows pectoral fin in Figure.1 that will brush up latently inside recuperation stroke that can prompt to decreased drag-compel. On the other hand mechanical plug can misfortune the fin all through the office stroke, to constrain it to take after the endorsed movement of servo [18], [19]. Thus, by arranging grants to the fin to give web push even once the servo motor is persuaded to move its arm front and back symmetrically, against very surprising recuperation and power stroking speeds are required inside instance of an inflexible fin joint [20], [21]. The unbending fin is associated with the joint system of the fin opening besides secured to wires through made gaps on fin-mounting structure [22].

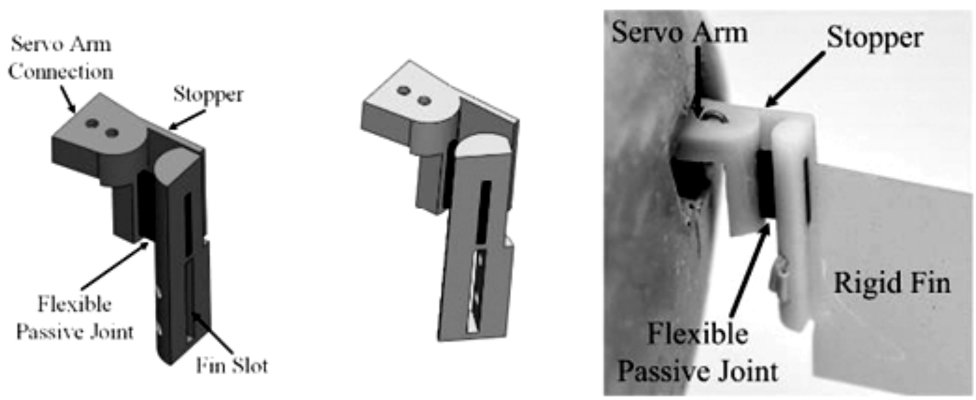


Figure 1: (a)During Power stroke (b) During Recovery Stroke (c) 3D Joint printed

2.2. Dynamic working model

The examination and advancement of detached fin joint component, which is a dynamic model of mechanical fish consolidating such instrument is required. Surrounding this work, they tend to consider an automated fish with rigidity of the body which has unbending pectoral fins attached to the base instrument by the flexible uninvolved joints, encased due to incompressible fluid. The automated body movement of fish shows the inflexible body progression with additional mass being fused. Cutting edge segment hypothesis is utilized to judge the liquid mechanics power produced by the pectoral fin's movement [13], [23].

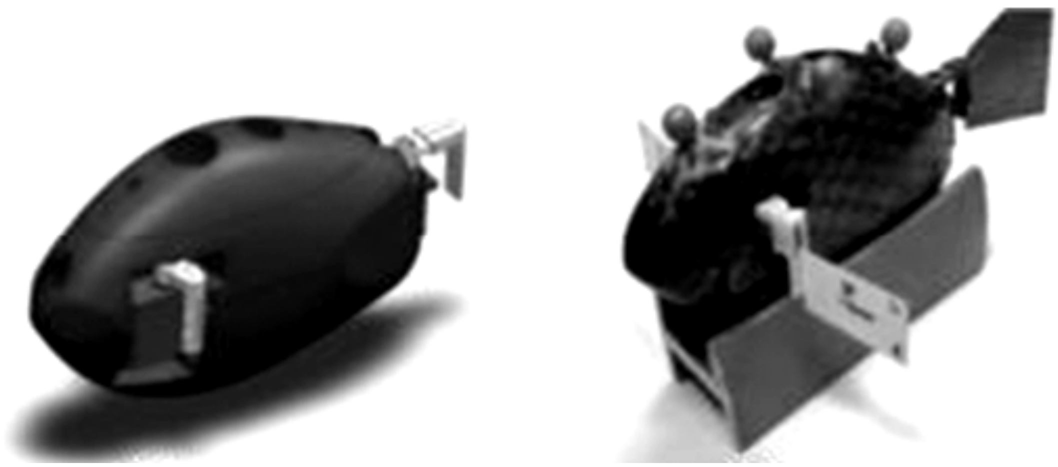
2.3. Robotic Fish Prototype

To assess the anticipated flexible fin joint component and approve the given element display, they've conducted examinations on an unattached automated fish picture. Concerning about fin joint models, the individual's constitution of the robotized fish picture could have been portrayed to solid works in Figure.2. [25], [26].

2.4. Dynamic model validation

For evaluating the individual evolving model, drag in addition raise coefficients, Compact disc, CL, and CM square measure identified through correct discernment for a relative computerized fish with an endeavor of unyielding pectoral fins that square measure related determinedly of the servo arms (rigid joint), on each ahead swimming likewise turning developments. Extraordinarily, they've tuned these parameters ought to further bolstering the turning range, turning total, Moreover ahead pace. Previously, reenactment on 2 frequencies (with the individuals working nature's domain stroke pace of the pectoral fins around make similar. Previously, light of the way that the compel stroke speed of the biracial flapping fins in specific situation 5 Hz Additionally 2. 5 Hz) in this course used a practically undefined twin coefficients for the individuals occurrence starting with guaranteeing flexible joints.

Min Tan et al. proposed modelling of a flexible, passive joint for a pectoral fin that enables net thrust generation under symmetric actuation of a single rowing actuator in power and recovery strokes. Flexible joints of the pectoral fin to sweep back passively during the recovery stroke, following the motion prescribed by the actuator during the power stroke. Consequently, fin experiences less drag in the recovery stroke than in power stroke, resulting in net thrust [27], [28].



(a) (b)

Figure 2: (a) Design Solid Works model (b) 3D-Printed Model.

Specifically, the activation with both pectoral and caudal blades will bring about a generally high speed for the mechanical fish body [29]. Subsequently, the approach for pectoral blades will never again be near 90æ% and the traverse insightful part of the pectoral balance constrain should be fused. In the creators elective outline of adaptable joints for pectoral blades was proposed, where the balance would experience an uninvolved feathering movement amid the recuperation stroke. Another fascinating examination heading will investigate the cooperation between the adaptable caudal blade and the pectoral balances. In this case the caudal balance can be considered as an impetus source to empower a higher swimming velocity, while the pectoral balances are utilized for precise tuning and controlling [30].

3. DESIGN AND MOTION CONTROL

Cheng Zhang et al. proposed a sans model movement administration approach for an automated fish. The fish-like swimming steps are created by general inner model GIM type learning approach for the robotization at Figure 4. At that point, feedforward controller and a corresponding indispensable subsidiary PID based input controller are planned to direct the swimming walks of the robot to accomplish craved movement in Figure 3. To help the execution of the criticism controller and keep away from dull manual alignment, an unadulterated information driven re-iterative input IFT type of approach is embraced for adjusting the parameters of the input controller [3].

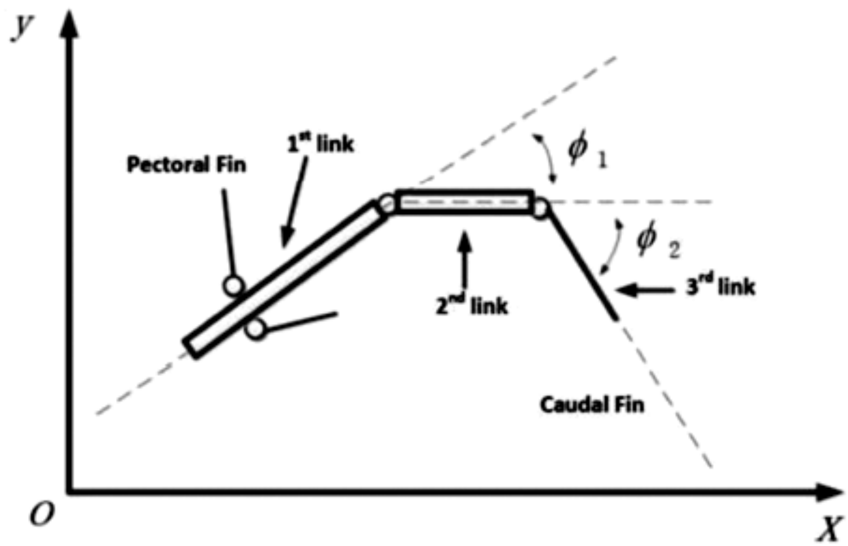


Figure 3: The fish model with multi joint

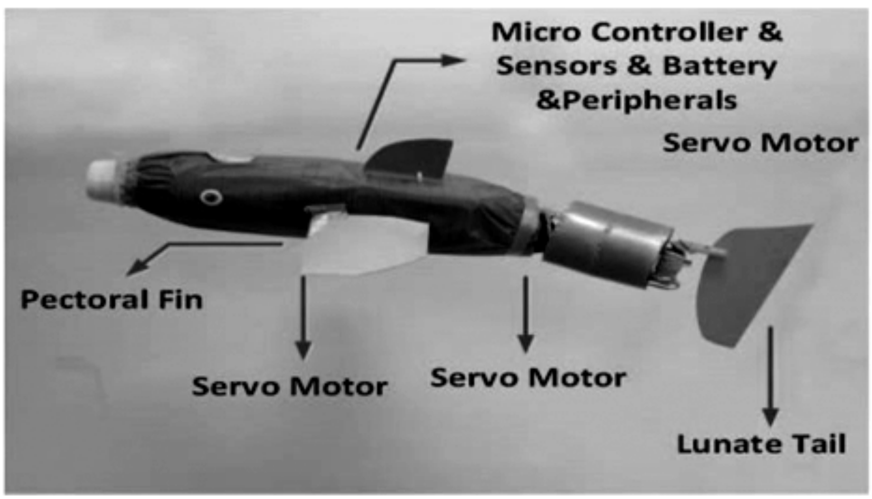


Figure 4: Structure for robotic fish.

3.1. Fish like swimming jaits generation-

GIM type of learning methodology used for creating the swimming velocity modes inside the automated fish. In investigation on every swimming movement mode might be portray as gathering of facilitated developments in fish exertion components, that is extricated from discerning a live carangiform fish swims by a fast recording framework. The development created by exertion components might be learnt and recovered by a GIM. From Figure.5. GIM comprises of 3 sections. The first part is generator that produces maintained occasional signs to energize the GIM. The next part is AN ANN inside the example learning strategy, the mechanical wonder of the exertion components development is given in light of fact that the coveted development for the ANN training. Long Wang proposed movement administration for one very submerged mechanical fish is given amid this paper. Here our mechanical fish illustration has 2 long-blades put in symmetrically on its either side. Also, one long-blade is framed up by spring layer covered on 10 beam balances. 10 servo-motors are utilized to deal with the movements of the 10 beam balances on one side to the extraordinary structure of the illustration, swim movement modes is broken into four essential movement modes: walk mode, subsiding mode, pivoting mode and side influencing mode. Controller is predicated on FPGA. Through perusing signal information keep inside

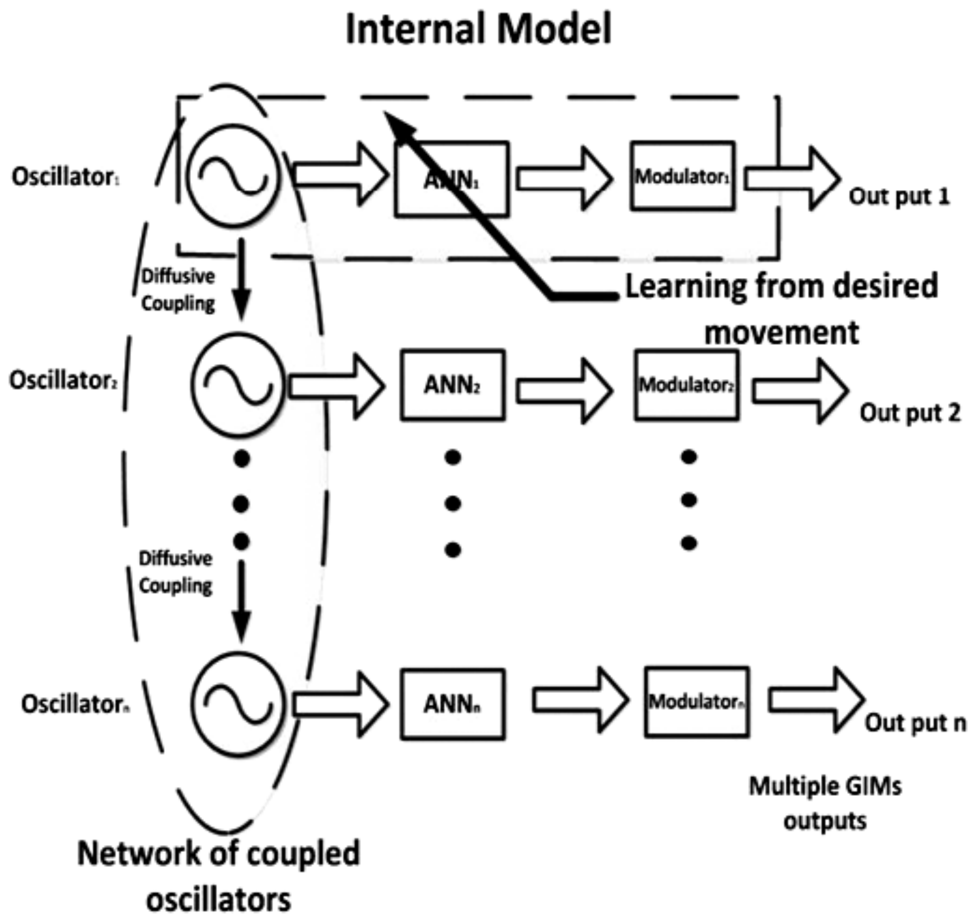


Figure 5: Coordination of complex movements output by multiple GIMs.

the memory of administration chip, servo-motors could sway beam balances at consistent approach. Accordingly, entirely unexpected recurrence and diverse area qualification of adjoining beam blades could twist the long-balance designed by film into significant wave. As an after effect of the layer is delicate and flexible liquid mechanics strengths made by removed water could drive angle body into swimming movements. Automated fish could switch its movement mode by the moved one in swimming [2].

3.1.1. Robotic fish prototype

This fish has exclusively a broadened blade while not balance and ventral balance as shown in Figure 6. Swimming is accomplished by that of twisting the dorsal in accordance with half suspense structure whilst its physique continues away best along. The dorsal shows bunches concerning glow balances (up in accordance with 183-230). Along these lines from very surprising part mix of the beam balances, fish body movement in various directions is accomplished. These blends can be horrendously grave to get and hydro dynamics is amazingly complex. At that point a mechanical fish encapsulation is planned and created for the long-blade impetus investigation. The exemplification demonstrates that automated fish comprises of fish body, 2 long-balances. Angle body is framed by fiber reinforced plastic has put in 10 servo motors symmetrically. Its framework depends on the FPGA being used as shown in Figure.6. First system send order from radio modulator. At that point automated fish's controller gets order and skim applicable information keep in FPGA chip. Next phase controller send these information to servo-motors exclusively Figure 7. At long last servo-motors drive the long blade to finish impetus [6].

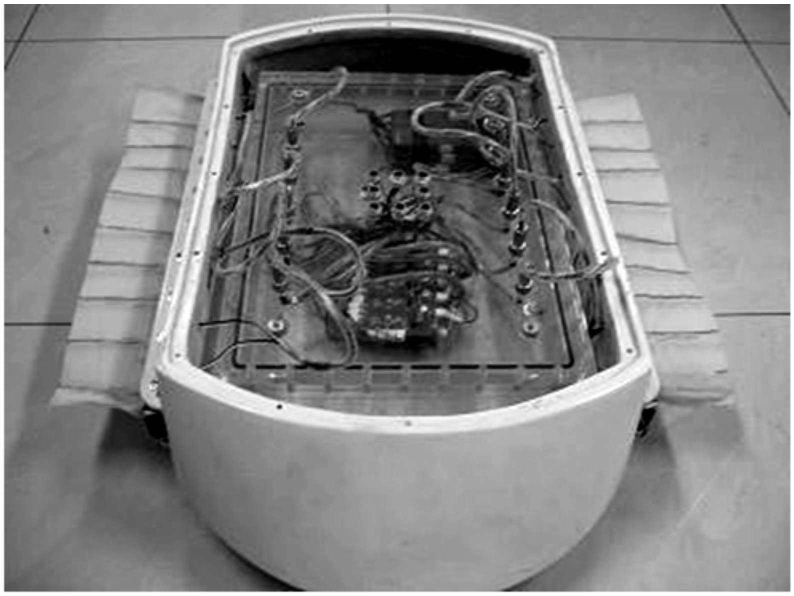


Figure 6: Robotic fishprototype

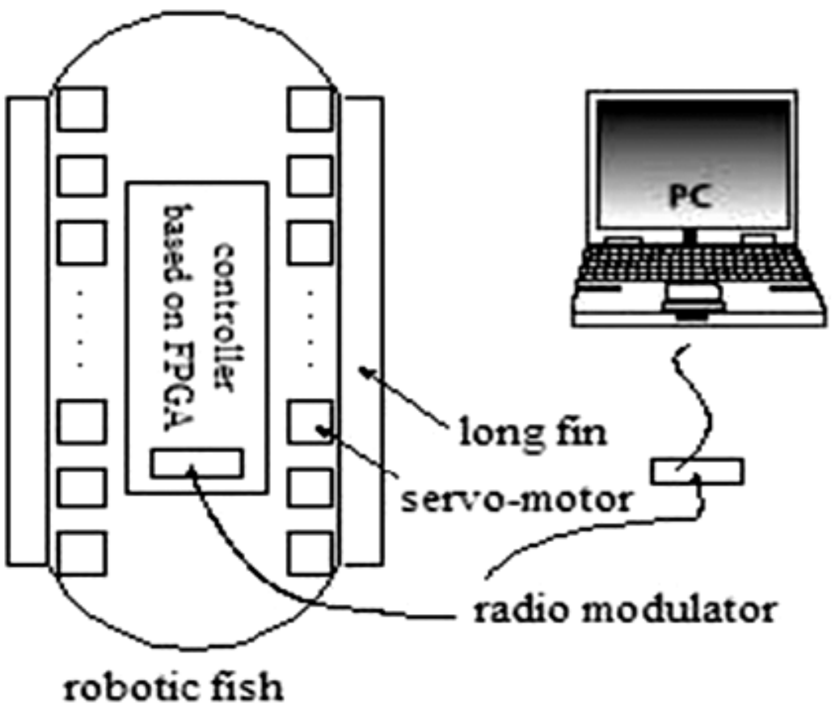


Figure 7: Control system for robotic fish

3.1.2. Remote movement

Remote may be radio modulator connected with compact PC. At first tablet sends signals by the radio modulator. By then another radio modulator put in on mechanized fish gets the regulated flag and demodulates it for the controller chip. Finally, the controller unravels the flag and changes over into couple orders predefined by Joined States of America. Our charges embody most of the development modes said on top of concurring the charges, controller will drive servo engines and execute operations.

3.1.3 Motion Modes Switch System

As specified on top of their movement modes in which switch framework utilizes Mega128 as controller. At the point when getting charge for switch movement modes, Mega128 will decode order and exchange it to controller upheld FPGA. Figure.8 demonstrates working strategy. Mega128 has keen capacity to get signals from radio modulator and exchange information to FPGA. This technique may spare assets of FPGA. It can likewise fabricate our controller more straightforward and less demanding. Through programming Mega128, order flag might be accomplished, then exchange it by fast level interpreter unit. Next controller examinations will measure voltage level blend and contrast and then program for FPGA.

Sanaz Bazaz et al. proposed a quick swimming robotic fish capable of high mobility and by with less joints. In particular, related enhanced mechanical structure enriches the component with goliath push and overstated shift of developments. Movement investigation offers accommodating guiding to parameter settings of unfaltering swimming. Submerged tests on straight swimming and very surprising turns exhibit the viability of the arranged ways and mechatronic styles. Utilizing the swimming execution appreciate genuine fish as a guide either on expanding propulsive speed or on improving mobility [6].

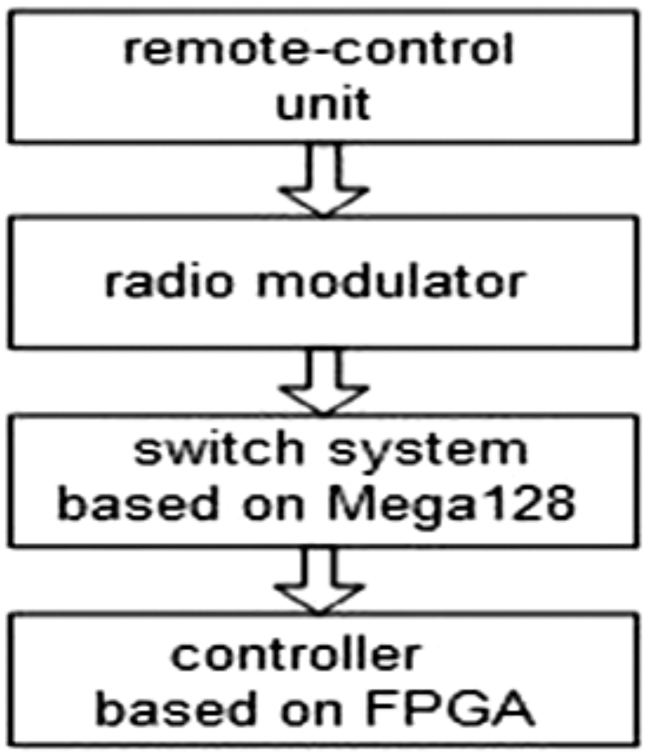


Figure 8: Motion modes switch system

3.1.4. Design of robotic fish

To make an automated fish fit for forward swimming and with less joints, He gave a solitary engine impelled style subject that receives a two-joint mechanical arrangement. From the state of mind of zoology, brisk swimmers satisfy the body or potentially caudal balances BCF mode will exhibit a few attributes and in addition to its relatively inflexible bodies, unbending semilunar tails, and thin peduncles. In addition, the measurements of different components of the automated fish is upgraded. Most importantly, the starting position of the essential joint is changed to 2/3 position of total fish body that will be considered to be an enhanced segment to reduce wavering sufficiency of fishhead [3].

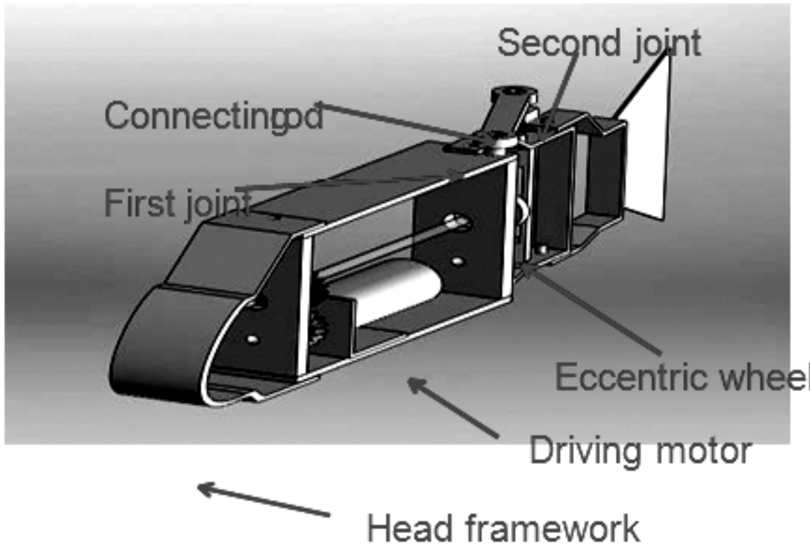


Figure 9: Mechanical structure of modified fish.

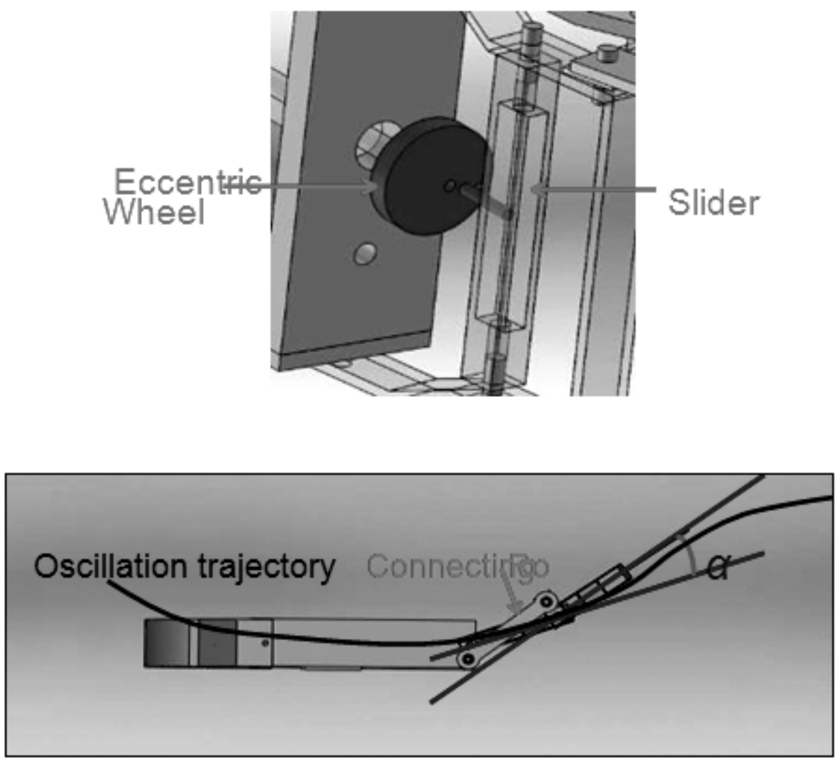


Figure 10: Mechanical structure of the 2nd joint.

They have a tendency to show that single-motor designed automated fish will be like rearranged mechanical structure and movement management in such a manner as enhanced general execution. Along these lines, the anticipated mechanical fish subject reveals new look of insight weight on activity of every brisk swimming and mobility on indistinguishable at automated stage, in like manner on the grounds that the improvement of building is on focused substantial scale of mechanical instrumentation in Figure.10. In future, this had a tendency to choose to keep ascending from precursor created mechanical fish and administration routes by consistence elements and best administration [3].

Xuefang Li et al. proposed that there are two sorts of swimmers: BCF swimmers which can swim with their body and caudal adjust, MPF swimmers deliver push with center and coordinated cutting edges. In the area of bio mechanical AUV, both sorts of swimming modes have been used in mimicked systems. Under water is the one segment for development control from Figure.11 [6].

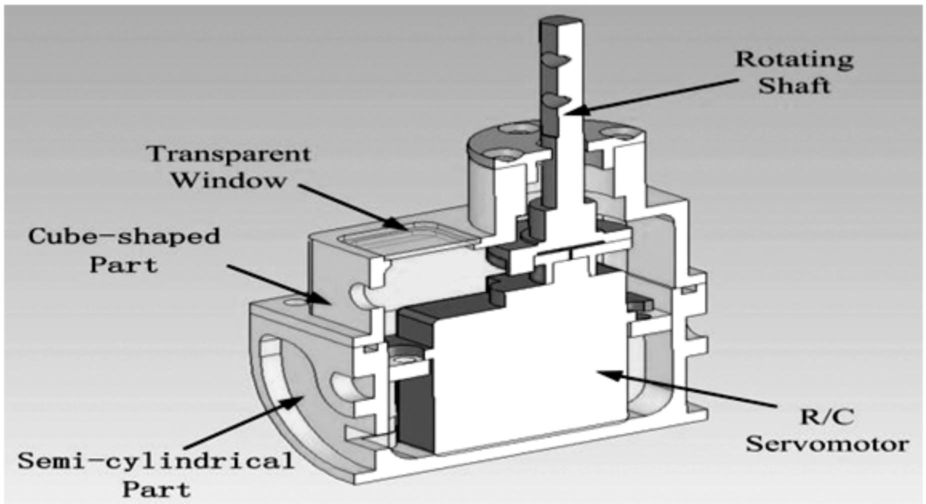


Figure 11: Intersection view of Pectoral Fin Module

Secluded automated fish is intended with expectation of complimentary swimming to an extent that it is furnished with on board control, inserted microcontroller and remote correspondence module. Four rechargeable NiCad cells of 2500mAh limit give the automated fish around one hour control self-rule. The movement of automated fish is controlled by microcontroller named AT91SAM7A3 that fuses a superior 32-bit RISC,

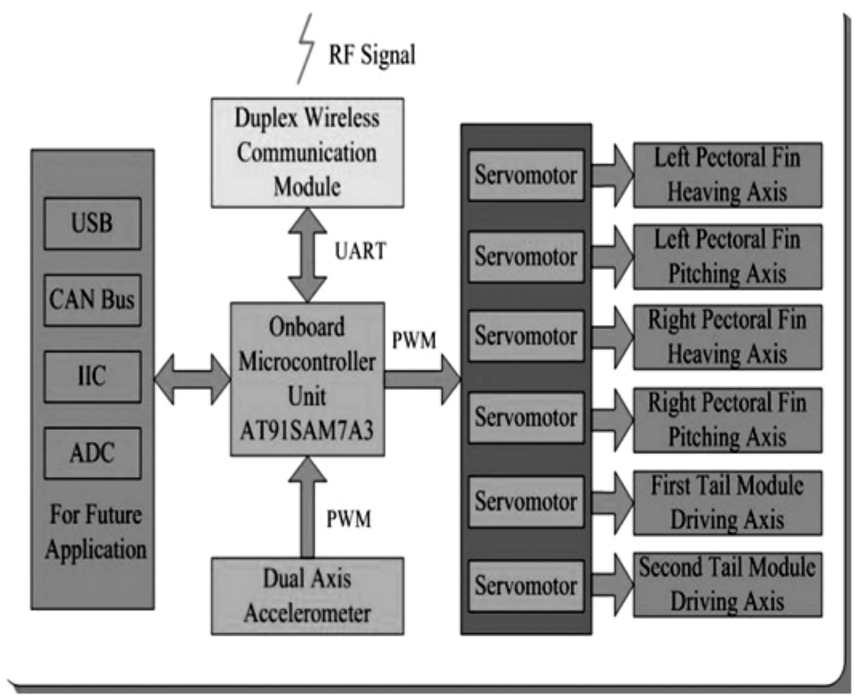


Figure 12: Hardware Architecture of Control System

ARM7TDMI processor and an extensive variety of peripherals from ATMEL Enterprise. The controller associates remote correspondence module through UART port. A double hub accelerometer ADXL202 is utilized to gauge the increasing velocities in the pitch and move tomahawks. The R/C servomotor has inward position criticism and the level of the turn of the hub relies on the information PWM (Beat Width Regulation) flag. The microcontroller creates six PWM signs to control movement of joints and gets no criticism flag. The proposed model is in form of block diagram [5].

A supplanting sensibly mechanical fish with 2 undulating long-blades is presented. The undulating long-blades will create push to drive the mechanical fish. Four fundamental movement methods of the mechanical fish are anticipated and portrayed. The key modes grasp Walk mode, retreating mode, pivoting mode and side-influencing mode. Going for these fundamental modes, administration systems to servo-engines are presented exclusively. Remote with the radio modulators, we have a tendency to do the analyses of 4 movement modes. The examinations demonstrate the execution of those movement methods of the mechanical fish using iterative feedback controlling [1].

4. SPEED

Xiabo Tan et al. Proposed on p-sort ILC (iterative learning control) algorithm. It is a path based on algorithmic standards.

An exact speed controlled approach for a two-interface automated fish is proposed. To accomplish ideal speed direction , They built a scientific model for two-interface carangiform for automated fish as indicated by the Lagrangian mechanics strategy by uprightness of the structure of the built dynamical model, a P-sort ILC calculation is created. The union investigation of the proposed ILC plan is inferred. The productivity of the proposed control calculation is not just showed by mimicking and confirming through exploratory outcomes. It is demonstrated that ILC is a best control approach for the movement control of mechanical fish as a result of its model free property and the effortlessness of the calculation persuaded by their adequacy in the speed control [7].

Jian-Xin Xu Proposed stream identifying while the robot is uninhibitedly swimming while a nonlinear model to expect energetic swimming rate of robot. Undeniably, we use nine weight sensors to circle around the body and use an inertial estimation unit IMU to screen kinematics to gage speed of a wholeheartedly swimming

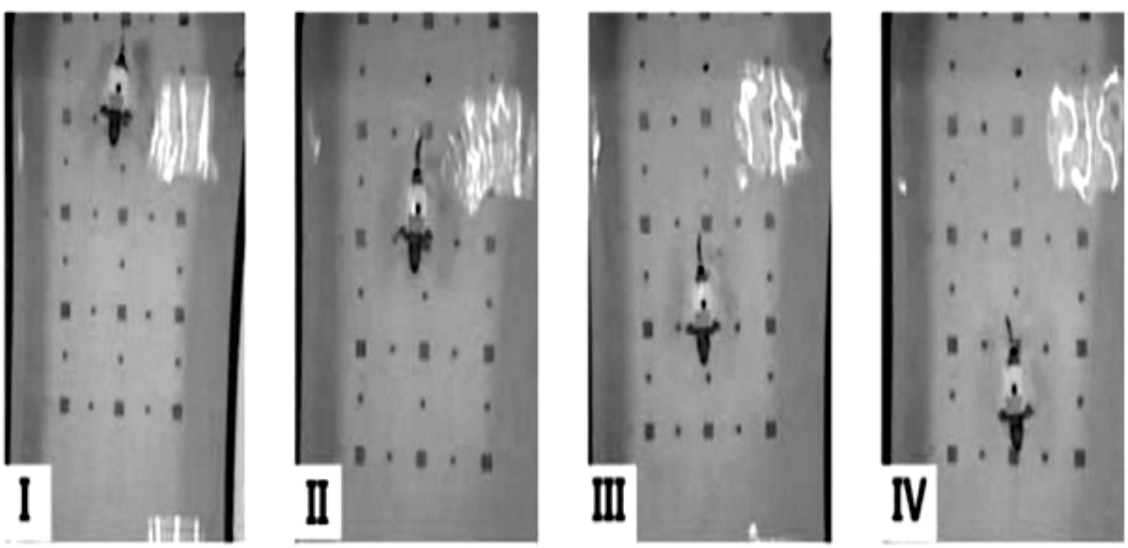


Figure 13: Trajectory Path Speed trajectory ($Vd(t) = 48 t^2 (t-50)^2 / 50^5$).

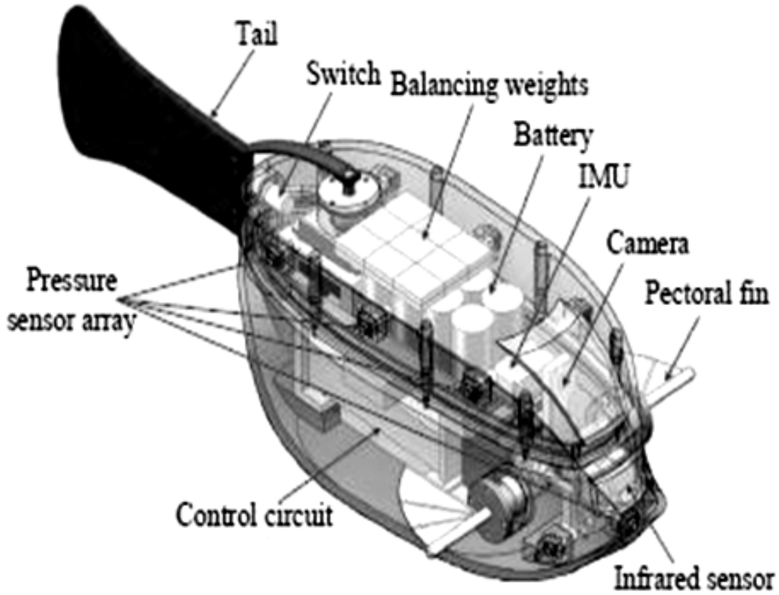


Figure 14: Mechanical Structure and Electronics of Robotic Fish

robot. Through examination, we can find that both direct speed and oscillatory development of robot added to disperse weight during straight forward swimming. At that point a nonlinear Figure.14 indicates the united scattered weight and the influence of dashing velocity to assess the speed of the robot. Online speed appraisal tests shows the exactness of the display [9].

Concentrating on more convoluted movements helped by fake horizontal line is of its awesome centrality to uncover significant fish parallel line detecting and in addition to this enhancementof the sensor practicability. It utilizes a simulated side long line to unequivocally calculate speed of a swimming robot. Huge investigations were led with unreservedly swimming automated fish. Examining disseminated weight, movement kinematics information and speed of robot, we found that both direct speed and oscillatory rakish speed is added to deliberate weight. We can likewise propose a nonlinear expectation model to assess speed of mechanical fish. Online speed assessment with model shows the effectivity and the precision of proposed speed forecast. In accompanying review, they utilized counterfeit horizontal line to assess swimming velocity while robot is turning. They concentrated on speed adjustment and arranging with robot utilizing created manufactured sidelong line-based speed assessment show [7].

Wei Wang et al. proposed from heartbeat reactions that the automated fish has a postponed pushed term, which strongly affects the control execution. By direct analyses to acquire beat reactions, the impact of the defer term can be computed. Another imperative Figure.15 push displaying is the nonlinear mapping from tail wavering abundancy to the edge level. Step reactions at enduring state give test information that can Figure this nonlinear mapping. With the information displayed, sliding mode control is built as an exceedingly dependable modelbased controller for the mechanical fish to track a period changing reference. Correlations are led tentatively for robot speed control in four situations individually with both push postponement and nonlinearity, with push defer just, with push nonlinearity just, and with neither of push postponement and nonlinearity [8].

This describes the platform hardware structure of robotic fish and explores, develops the data-assisted model for the robotic fish dynamics with the two essential elements of thrust delay and nonlinearity. Model based discrete-time SMC is designed.

They presented a data-assisted modelling method for the motion control for two-link robotic fish. The need for such a data-driven approach arises from the complex hydrodynamics that makes any analytic modelling

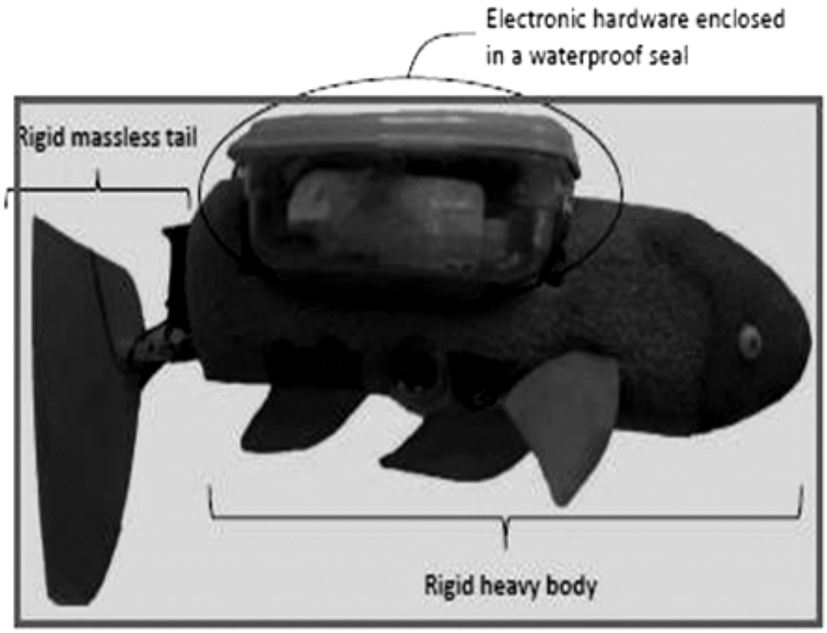


Figure 15: Physical Side View of Robotic Fish

of the thrust mechanism impossible. They proposed pulse-based identification for thrust delay, and step response based identification for thrust nonlinearity. Next, sliding mode for control design is presented for robot fish when it performs speed control. Further, it is experimentally compared and verified that the delay and nonlinearity are essential for improving the controller performance [9].

5. VISION BASED SELF CONTROL OF ROBOTIC FISH

Robotic competitions are ideal benchmarks for artificial intelligence analysis. Wei Wang proposed to introduce a category of robotic fish competitions that use biometric robotic fish to play water polo like games. In such competitions, the boxfish-like robots use their aboard cameras to amass setting data and overhead global-vision camera is taboo. To win the sport, many issues like self-localization, underwater motion management, underwater communication, and multiple underwater golem cooperation got to be investigated. The competition will promote the underwater robotics and their applications [10].

5.1. Mechanical System

It consists of main module, a try of pectoral fins and a caudal fin. The module of robotic fish is intended within the style of sealed shell. Reversible battery, sensors and motors are wrapped within the shell. The shell is created from 2 elements. The higher half is created of plastics ABS. The lower half is created of aluminum. Static seal and motive seal were used to ensure the sealing property of the robotic fish. Seal rings and grease are used for the waterproofing property of rotating shafts. The fins are designed basing on the form of the important fins. The density of robotic fish had been labelled to come near to the density of water. In order that it's ready to float on the surface of the water from Figure.16. The robotic fish implements forward movement and turning action by dominant the swing caudal fin [10].

5.2. Electrical System

The electrical system is vital for the robotic fish as shown in Figure.17. The perception of the external atmosphere, the process of processor, and also the management of actuators square measure all supported to the electrical

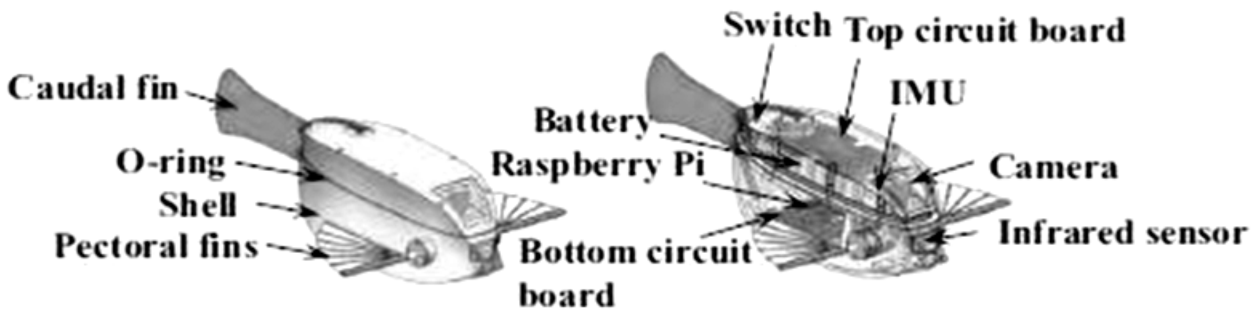


Figure 16: Configuration of Robotic fish

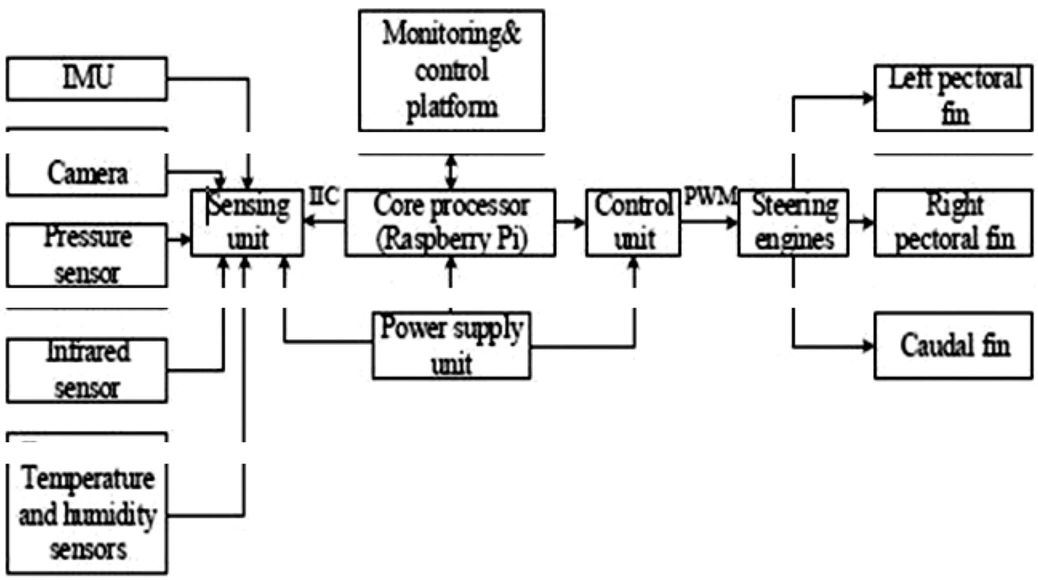


Figure 17: Electrical robotic fish system

system. It consists of power provide unit, sensing unit, management unit, driving and management platform, processor, and so on. The electrical system is made supported Raspberry Pi that is that the core processor. Raspberry Pi may be a card sized miniature electronic brain. The system put in on Raspberry Pi is Linux. With the utilization of Raspberry Pi, the robotic fish is in a position to be operated autonomously through Linux management unit receives motion commands from the processor, then controls the running of steering engines. Management unit relies on CPG management model which may generate many totally different forms of PWM waves. These PWM waves have a precise delay within the section. Input these PWM waves to steering engines that management the pectoral fins and caudal fin, we will management the robotic fish's numerous motion modes.

5.3. Software system for the competition

5.3.1. Basic principle

We have designed associate open experimental platform that has characteristics of friendly graphical interface, modularized software package style, and period of time image process. Additionally, it has the excellent function of recording and replaying experiment results. The experimental platform insists for the robotic fish scheme, the communication scheme, and also the laptop observance and management platform. By establishing the operation system platform that is predicated on UNIX operating system. With the assistance of intelligent sensors, the aptitude of autonomous sensing has improved. Additionally, the robotic fish will communicate with stable and reliable Wi-Fi. It will transfer pictures to the driving and management platform in period of time through Wi-Fi [10].

5.3.2. Human Machine Interaction

In order to understand the observation and management of the robotic fish, we've got designed the observance and management platform as shown in Figure. 18. The platform may be accustomed implement the parameters displaying, parameters adjustment, speed measuring and movement management of robotic fish. The platform is principally composed of five major elements that area unit showed in Figure.18 space I represents image-display space. Space II represents sensing element data-display space. Space III represents network-setting space. Space IV represents parameter control space. Image-display area: Camera equipped with the robotic fish is employed to gather the image data below the water. And therefore the data may be transmitted to the higher observance platform through Wi-Fi, in order that the image are going to be displayed in image-display space. Sensing element datadisplay space: this area is principally accustomed show the info collected by the sensors put in within the robotic fish. These sensing elements embrace infrared sensor, pressure sensing element and terrorist organization [10].

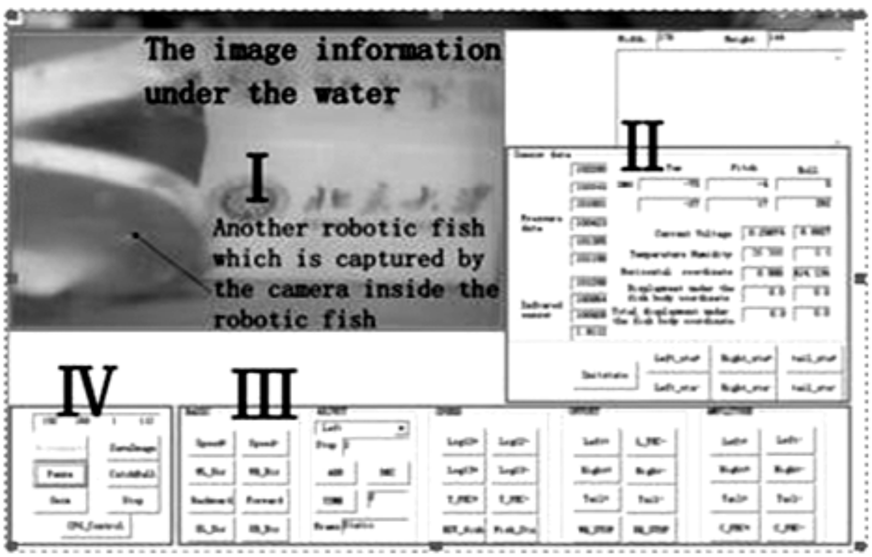


Figure 18: The computer monitoring and control platform of the robotic fish.

6. CONCLUSION

We can concludethat by surveying the papers on robotic fish can be designed and controlled in many ways from the above papers and new such methods can improvise the performance of robotic fish. By following such methods the robotic fish design we can improve speed and we can improve the path trajectory that will make easy to control the robotic fish easily. From vision form of self analyzation of data makes the robotic fish to enhance their ability to sense conditions and will make more data though this process in real time .So, here we can use those methods for controlling the motion of the fish and analysis of the data obtained from the robotic fish and can be used to sense the conditions and monitor the conditions under water.

REFERENCES

[1] Qinyuan Ren, Jianxin Xu, and Xuefang Li , C.: A Motion Control Approach for A Robotic Fish with Iterative Feedback Tuning. In: IEEE International Conference on Industrial Technology (ICIT),pp. 40-45,2015.

[2] Liuji Shang, Shuo Wang, Min Tan, Xiang Dong Li, C: Motion Control for an Underwater Robotic Fish with Two Undulating Long-Fins In: Proceedings of 48th IEEE Confrence,pp. 6478-6483,2009.

[3] JunzhiYu;ChengZhang;LianquingLi Li , T: Design and Control of a Single-Motor- Actuated Robotic Fish Capable of Fast Swimming and Maneuverability In: vol. 21,pp. 1711-1719,2016.

[4] Yonghui Hu;Long Wang;Wei Zhao;Qi Wang;Le ZhangLi , C: Modular Design and Motion Control of Reconfigurable Robotic Fish In: 46th IEEE Confrence on decesion and Control,pp. 5156-5161,2007.

[5] SanazBazaz Behbahani;Xiaobo TanLi ,T: A Flexible Passive Joint for Robotic Fish Pectoral Fins: Design, Dynamic modelling and experimental results In: 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems,pp. 28322838,2014.

[6] XiaoboTan;SanazBazazBehbahaniLi, C:Design and Modeling of Flexible Passive Rowing Joint for Robotic fish pectoral Fins In: IEEE Transactions on Robotics,vol. 32,pp. 1119-1132,2016.

[7] XuefangLi;QinyuanRen;JianXinXuLi, C:Speed Trajectory Tracking of A Robotic Fish Based on Iterative Learning In:Control Conference (ASCC),pp. 1-6,2015.

[8] Wei Wang;Yuan Li;Xingxing Zhang;Chen Wang;Shiming Chen;Guangming XieLi ,C:Speed Evaluation of a Freely Swimming Robotic Fish with an Artificial lateral line In: 2016 IEEE International Conference onRoboticsand Automation (ICRA),pp. 4737-4742,2016.

[9] Saurab Verma;Jian-Xin XuLi , C:Data Assisted Modelling and Speed Control of a Robotic Fish In: IEEE Transactions on Industrial Electronics,pp. 1-1,2016.

[10] XingwenZheng;WeiWang;ChenWang;Ruifeng Fan;Guangming XieLi ,C:An Introduction of Vision-Based Autonomous Robotic Fish Competition In: 2016 12th World Congress on Intelligent Control and Automation (WCICA),pp. 2561-1566,2016

[11] J . N. Newman and T. Y. Wu, Li, C:Hydromechanical aspects of fish swimming, In: Swimming and Flying in Nature, T. Y.-T. Wu, C. J. Brokaw, and C. Brennen, Eds. Springer US, Jan. 1975, pp. 615–634.

[12] Saurab Verma; Jian-Xin Xu Li, C: Data Assisted Modelling and Speed Control of a Robotic Fish In:IEEE Transactions on Industrial Electronics,pp. 1-1,2016.

[13] X. Tan, D. Kim, N. Usher, D. Laboy, J. Jackson, A. Kapetanovic, J. Rapai, B. Sabadus, and X. Zhou, Li, C: An autonomous robotic fish for mobile sensing, In: IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2006),Beijing,China,Oct.2006,pp.5424– 5429.

[14] K. A. Morgansen, B. I. Triplett, and D. J. Klein, Li, C: Geometric methods for modeling and control of free-swimming finactuated underwater vehicles," IEEE T Robot, vol. 23, no. 6, pp. 1184–1199, Dec. 2007.

[15] S. Guo, T. Fukuda, and K. Asaka, Li,C:A new type of fish-like underwater microrobot, In: IEEE-ASME T Mech, vol. 8, no. 1, pp. 136–141, Mar. 2003.

[16] K. H. Low, Li, C:Locomotion and depth control of robotic fish with modular undulating fins, In: Int J Automat Comput, vol. 3, no. 4, pp. 348–357, Oct. 2006.

[17] XingwenZheng;WeiWang;ChenWang;Ru ifeng Fan;Guangming Xie Li,C:An Introduction of Vision-Based Autonomous Robotic Fish Competition In: 2016 12th World Congress on Intelligent Control and Automation (WCICA),pp. 2561-1566,2016.

[18] J. Yu, M. Tan, S. Wang, and E. Chen, Li,C:Development of a biomimetic robotic fish and its control algorithm,In:IEEE T Syst Man Cy B, vol. 34, no. 4, pp. 1798–1810, Aug. 2004.

[19] Z. G. Zhang, N. Yamashita, M. Gondo, A. Yamamoto, and T. Higuchi, Li , C:Electrostatically actuated robotic fish: Design and control for highmobility open-loop swimming, In: IEEE T Robot, vol. 24, no. 1, pp. 118–129, Feb. 2008.

[20] X. Tan, Li , C: Autonomous robotic fish as mobile sensor platforms: Challenges and potential solutions,In: Mar Technol Soc J, vol. 45, no. 4, pp. 31–40, 2011.

[21] S. Marras and M. Porfiri, Li , C: Fish and robots swimming together: attraction towards the robot demands biomimetic locomotion,In: J R Soc Interface, vol. 9, no. 73, pp. 1856–1868, Aug. 2012

[22] M.Aureli,V.Kopman,andM.Porfiri, Li ,C:Free-locomotion of underwater vehicles actuated by ionic polymer metal composites, In: IEEE-ASME T Mech, vol. 15, no. 4, pp. 603–614, Aug. 2010.

[23] J. Wang, P. K. McKinley, and X. Tan, Li,C:Dynamic modeling of robotic fish with a flexible caudal fin,In: ASME 5th Annual Dynamic Systems and Control Conference joint with the JSME 11th Motion and Vibration Conference (DSCC2012MOVIC2012). Ft. Lauderdale, Florida: American Society of Mechanical Engineers, Oct. 2012, pp. 203–212.

[24] M.Montemerlo,S.Thrun,H.Dahlkamp,D.Stavens,andS.Strohband, Li, C:Winning the darpa grand challenge with an ai robot," In: Proceedings of the AAAI National Conference on Artificial Intelligence, vol. 1, 2006, pp. 982–987.

[25] W.Zhao,Li, C:Controlandcoordinationofmultiplebiomimeticunderwater robots (in chinese),In: Ph.D. dissertation, Peking University, 6 2009.

[26] W. Wang and G. Xie, Li,C:CPG-based locomotion controller design for a boxfish-like robot, In: International Journal of Advanced Robotic Systems, vol. 11, no. 87, pp. 147–169, 2014.

[27] P. Kodati and X. Deng, Li, C:Towards the body shape design of a hydrodynamically stable robotic boxfish,In: Intelligent Robots and Systems, 2006 IEEE/RSJ International Conference on, 2006, pp. 5412–5417.

[28] I. K. Bartol, M. Gharib, P. W. Webb, D. Weihs, and M. S. Gordon, Li, C:Body-induced vortical flows: a common mechanism for selfcorrective trimming control in boxfishes,In: Journal of Experimental Biology, vol. 208, no. 2, pp. 327–344, 2005.

[29] J. A. Walker, Li, C:Does a rigid body limit maneuverability? In: Journal of Experimental Biology, vol. 203, no. 22, pp. 3391–3396, 2000.

[30] W. Wang and G. Xie, Li, C: Online high-precision probabilistic localization of robotic fish using visual and inertial cues, In: Industrial Electronics, IEEE Transactions on, vol. 62, no. 2, pp. 1113–1124, 2015.