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Robotic Fish Tail Motion Excitation by Adaptive Control

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Abstract **- The objective of this work is to develop adaptive control for mechanical design of a biomimetic underwater vehicle. The aim is to construct vehicle control prototypes with propulsion mechanisms with the lowest possible complexity by using vibrations with adaptive control. This mechanical design can be then used to produce various gaits of locomotion in response to various hydrodynamic events.**

Success made in biological research mean we know much more about how animals survive, for instance deep-sea creatures' sensory organs or geckos' gravity-defying feet. The speed, power, and size of computers mean we can create programs that mimic neurophysiologic brain functions. Reverse engineering (tracking a result through its process to its source) has as a tenet that the cause exists. Therefore, just knowing there is an animal that can track moving objects while flying through space without visible light, proves that it's possible [1]. At present, the research in biomimetic underwater robotics has been partially driven by the necessity to develop more efficient, flexible, maneuverable, stable and adaptable vehicles capable of operating in a large variety of hard environments. The main driving force of the development is that the underwater vehicles in use today are designed for stable and open waters. These machines use propellers to generate thrust, and have very limited maneuverability.

Therefore, Biomimetic underwater vehicles are mainly needed for environments where good maneuverability, ability to produce thrust in many directions and rapid real-time control in response to sudden hydrodynamic events is a must. Rapid control and high maneuverability as well as the decreased scale are such achieved without an increased complexity.

Another advantage of the proposed mechanical design model is that it is fairly easy to model and control in real time. There is a good theoretical understanding developed over years about vibrations of elastic cords. It makes it possible to analyses the kinematics of the fin actuators and controls them. The control of the fish is then equivalent to finding appropriate excitation frequencies to produce the desired locomotion patterns.

Keywords **- biomimetic, robotics, fish motion, underwater vehicle, motion control, optimal synthesis, fish fin mower**

I. INTRODUCTION

During millions of years the result of natural elimination has created many unique underwater organisms, functioning of which is characterized by reliability, low energy consumption, precision, and rationality? Harmony of life, ability of organisms to adapt various changes of multiple factors of environment, diversity of adaptive reactions – all that sets up the richest collection of live samples for technical systems to be constructed.

Due to that the best result in construction of technical systems can be reached in bionics. It is possible to save a lot of time and efforts, if we use solutions found by nature during long selection process. Obviously there is no need for a blind following nature and thus denying human intellect to improve natural solutions.

Construction of underwater robots which use principles of motion of underwater organisms could solve following tasks of civilian and military use:

- Testing water quality and finding pollution sources.
- Testing integrity of underwater fuel pipelines.
- Finding large fish populations, providing commands to fishing vessels.
- Inspection of underwater parts of ships without presence of divers. Determination of ship hull fouling.
- Determination of marine stream velocity in different depth.
- Search for underwater mineral resources.
- Search for sunken ships and UXO’s.
- Passing through anti-submarine nets in ports, intelligence tasks, etc.

In order to perform similar tasks, a robot in a form of a fish needs to consist of following parts:

- strong load carrying hermetic body,
- mover,
- energy source,
- stabilization elements and control system,
- different types of sensors,
- devices for illuminating, photography, etc.

Robot needs to be supplied with artificial intelligence such as an on-board computer. Functions of the computer: information storage, memory of the motion control, signal output for correction of a motion, control of maneuvering.

II. REVIEW OF TASKS ALREADY PERFORMED

Search for bionic analogies started in 60’s of the 20th century, and soon become regular, systematic and large in scope. Experimental underwater devices with fin movers were created and investigated in 70’s – 80’s of the 20th century in the department of underwater moving devices. During recent years due to rapid development of calculation methods and control systems there are many interesting findings in the area of water and underwater robots, e.g. model of a swimming robot fish is described in [2].

Such models have two-sections of tail and remote control by a microcomputer. Sensing device allows for a robot to avoid obstacles. More sophisticated underwater robot (fish) was designed at the University of Washington and also has three parts: two sections of tail with a fin [3]. Robot has full autonomous control from power source and microcomputer, placed inside of the robot. The robotic fish is propelled by its tail and pectoral fins - these also enable the fish to swim in any direction, make tight turns and even go backwards. Underwater robot fish with a pneumatic drive was made in “Festo” company [4]. Electronics and pneumatics are hidden within its waterproof head and control the S-shaped movements of the tail fin via two fluidic muscles. Two further muscles are used for steering. The fin consists of an alternating traction and pressure edge.

High level research is performed in the United Kingdom, in University of Essex [5, 6]. The robotic fish has sensor-based controls and autonomous navigation capabilities – they can find their own way around the tank safely, avoiding the objects, and reacting to their environment. The robotics group at Essex is one of the largest in the UK and is at the cutting edge of research into human-centered robotics. Biological issues, hydromechanics of swimming, kinematics of motion of water organisms are described in [5, 6].

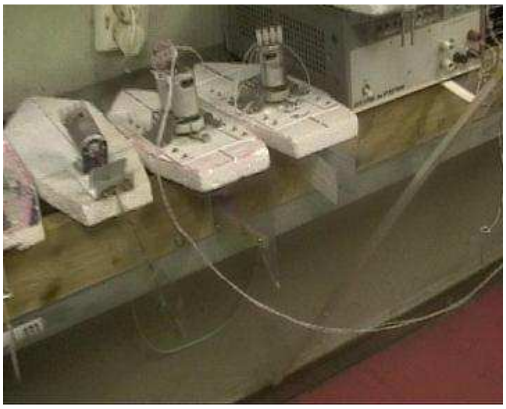

Fig. 1. Some devices of underwater robot in project “Filose”[1]

Fig. 2. Motion of non – autonomy robot inside small tank [1]

Investigations of robot fish swimming processes and constructions of new devices are at the starting positions in project “Filose” [1]. Some devices of underwater robot are shown in Fig. 1, 2. Additional theoretical and experimental investigations of Mechanical design in project “Filose” are given in [7 – 9].

The objective of the presented article is the usage of methods of theory of oscillations in mechanics and elaboration of new types of fin-type movers.

The initial stage of the research is discussed in case of a fin, placed on a mechanism moving in water.

Rather simplified system with one degree of freedom is investigated. It is assumed that mass and moment of inertia of the body are significantly larger than mass and moment of inertia of the fin. That allows by using of a simplified system to determine approximate results and to provide recommendations (Fig. 3).

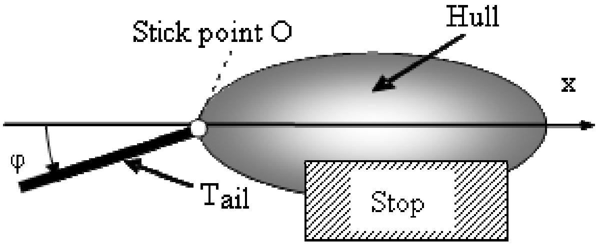

Fig. 3. Calculation scheme

III. FORCE ACTING TO A TAIL FIN

Initially forces and moments will be considered which are acting on the tail fin in still water.

Following assumptions are in use [8]:

- body 1(hull) is static and it is connected with the fin 2 over a joint O (Fig. 4, 5);
- In the joint there is another elastic restituting moment (spring) and also a moment generated by the drive, placed on the body to invoke oscillations (Figures 6, 7).
- tail fin is made as a rigid thin rectangular plate;
- forces of interaction of the fin with water depend from squared velocity in a local point (Figure 6);
- turbulent flow of the water is neglected;
- the motion takes place in a horizontal plane.

IV. EQUATIONS OF MOTION OF THE FIN

Differential equation of motion of the fin around z axis, directed through the point O, can be represented as (1) [10, 11]:

$$J_A\ddot{\varphi} = M(t,\varphi,\dot{\varphi}) - c\cdot\varphi - b\cdot\dot{\varphi} - k_t\cdot B\times$$

$$\times sign(\dot{\varphi}\cdot\varphi)\cdot\int_0^L\left(\dot{\varphi}\cdot\xi\right)^2\cdot\xi\cdot d\xi. \qquad (1)$$

Here J_A – moment of inertia of the fin in respect to z axis, directed through the point O;

$\ddot{\varphi}$ - angular acceleration of the fin;

$\int_0^L (\dot{\varphi} \cdot \xi)^2 \cdot \xi \cdot d\xi$ - integral to determine the moment of water resistance forces (Fig. 4);

L – length of the fin;

c, *b*, k_t, *B* – constant parameters.

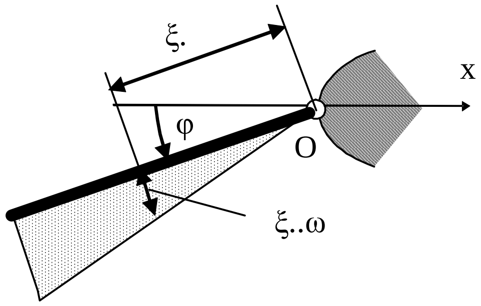

Fig. 4. Velocities in local points

From theorem of motion of the mass centre *m* of the fin along Ox axis it follows (2):

$$m \cdot \left(\dot{\varphi}^2 \cdot \frac{L}{2} \cdot \cos\varphi + \ddot{\varphi} \cdot \frac{L}{2} \cdot \sin\varphi \right) =$$
$$= Ox - k_t \cdot B \cdot \sin(\varphi) \cdot sign(\varphi \cdot \alpha\dot{\varphi}) \times$$
$$\times \left(\int_0^L (\dot{\varphi} \cdot \xi)^2 \cdot d\xi \right). \qquad (2)$$

After simplification from (1, 2) we get (3, 4):

$$\ddot{\varphi} = \frac{1}{J_A} \cdot \begin{bmatrix} M(t, \alpha, \dot{\alpha}) - c \cdot \alpha - b \cdot \dot{\alpha} + \\ + (-k_t \cdot B \cdot sign(\dot{\alpha}) \cdot \dot{\alpha}^2 \cdot \frac{L^4}{4}) \end{bmatrix}. \qquad (3)$$

$$Ox = m \cdot \{ \dot{\varphi}^2 \cdot \frac{L}{2} \cdot \cos(\varphi) + \frac{1}{J_A} \times$$
$$\times \begin{bmatrix} M(t, \varphi, \dot{\varphi}) - c \cdot \varphi - b \cdot \dot{\varphi} + \\ (-k_t \cdot B \cdot sign(\dot{\varphi}) \cdot \dot{\varphi}^2 \cdot \frac{L^4}{4}) \end{bmatrix} \cdot \frac{L}{2} \cdot \sin(\varphi) \} +$$
$$+ k_t \cdot B \cdot \sin(\varphi) \cdot sign(\varphi \cdot \dot{\varphi}) \cdot \dot{\varphi}^2 \cdot \frac{L^3}{3}. \qquad (4)$$

Thus, equations (3) and (4) allow approximate evaluation of action of the fin to the body (see Figures 3, 4.). If, for example, average value of the reaction in a steady state process is negative ($O_x < 0$), then the fin in average will pull body backwards. Oppositely, if $O_x > 0$, then fin will push the body ahead. In mathematical form it can be expressed as (5) [7]:

$$K = -\int_0^T \begin{pmatrix} m \cdot \{ \dot{\varphi}^2 \cdot \frac{L}{2} \cdot \cos(\varphi) + \frac{1}{J_A} \times \\ \begin{bmatrix} M(t, \varphi, \dot{\varphi}) - c \cdot \varphi - k_t \times \\ B \cdot sign(\dot{\varphi}) \cdot \dot{\varphi}^2 \cdot \frac{L^4}{4} \end{bmatrix} \times \\ \frac{L}{2} \cdot \sin(\varphi) \} + \\ + k_t \cdot B \cdot \sin(\varphi) \cdot sign(\varphi \cdot \dot{\varphi}) \times \\ \dot{\varphi}^2 \cdot \frac{L^3}{3} \end{pmatrix} \cdot dt, \qquad (5)$$

where *T* – time interval.

In this way by exchange of control moment $M(t, \varphi, \dot{\varphi})$ different criterion K may be obtained.

V. CONTROL ACTIONS

As example a harmonica excitation is in form:

$$M(t, \varphi, \dot{\varphi}) = M_0 \sin(kt),$$

were M_0 – constant amplitude.

Examples of modeling are shown in Fig. 5 – 7. Because full impulse is positive harmonica excitation will not be used for plane tail actuator drives.

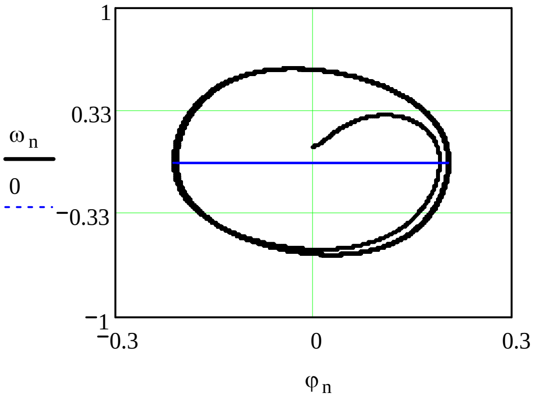

Fig. 5. Motion in phase plane for harmonica excitation

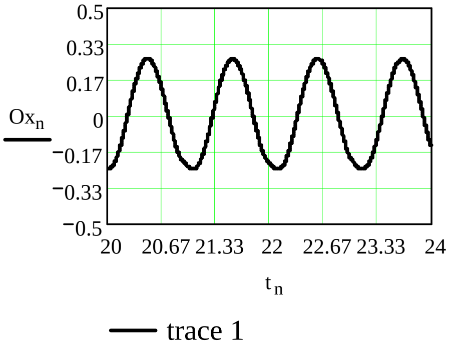

Fig. 6. Reaction *Ox* in contact point O

$$T_n := \sum_n Ox_n$$

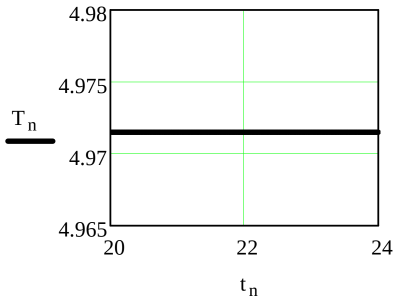

Fig. 7. Sum of full impulse in time domain (5). Impulse is positive and therefore will not be useful for plane tail

To get the most effective moment control, the control system must be organized with a feedback system, for example a proportional–integral–derivative controller (PID controller), that is widely used in industrial control systems. A PID controller attempts to correct the error between a measured process variable and a desired set point by calculating and then outputting a corrective action that can adjust the process accordingly, rapidly and effectively, to keep the error minimal.

Analysis of PID control shows that in this case is necessary to know three parameters: - proportional gain, - integral gain and derivative gain. By tuning the three constants in the PID controller algorithm, the controller can provide control action designed for specific process requirements. The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the set point and the degree of system oscillation.

The use of the PID algorithm for control does not guarantee optimal control of the system or system stability [12] unless adjusted properly. More efficient way of realizing optimal control is to use adaptive control as a function of phase coordinates form the equation:

$$M = M(\varphi, \dot{\varphi}) .$$

Two examples of adaptive control excitation in phase plane are shown in Fig. 8, 9, where M1, M2 and M0 are constant.

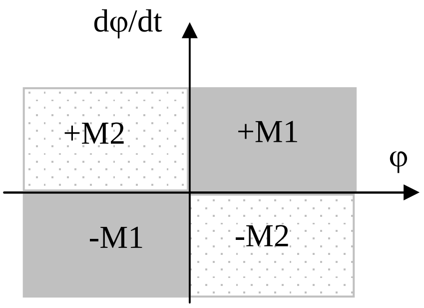

Fig. 8. Two level M1 and M2 adaptive control as two phase coordinates functions

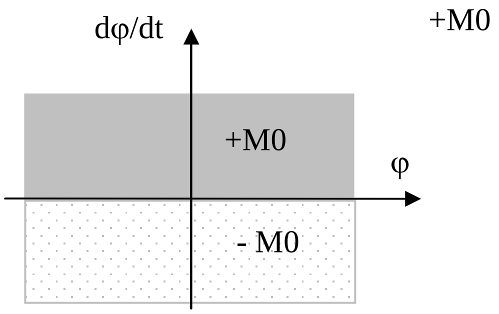

Fig. 9. Two level M0 adaptive control as one phase coordinates function

VI. SYNTHESIS OF REAL SYSTEM

In project [1] robot fish actuator with PID and adaptive control on the base of two solenoids was made (Fig. 10 – 12).

Fig. 10. 3D scheme of actuator with two solenoids

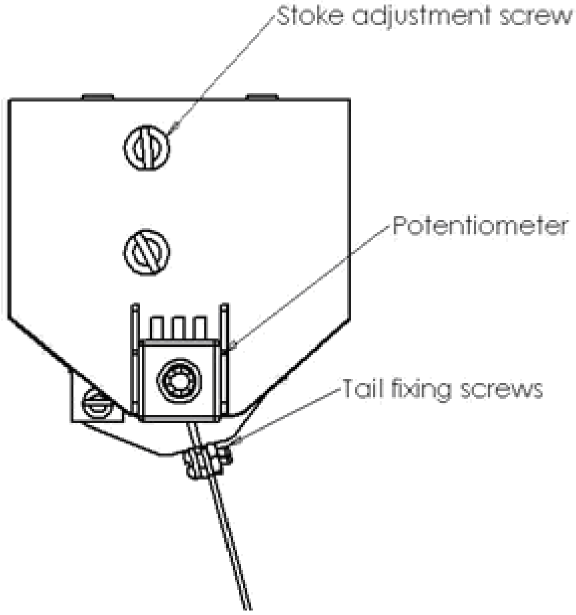

Fig. 11. For tail angle measurement actuator has potentiometer

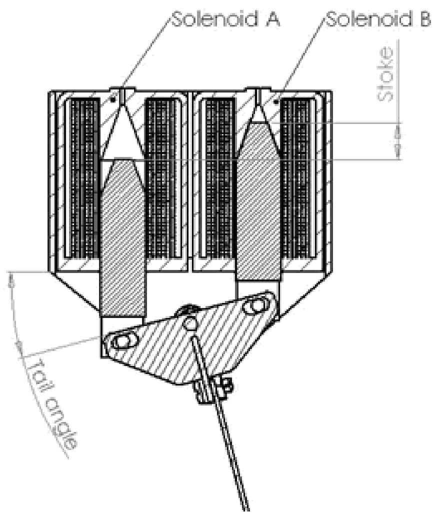

Fig. 12. Cross section of actuator with two solenoids A and B

Example of adaptive control moment as angular velocity function (6) was investigated.

$$M(t,\varphi,\omega) = M_0 \cdot sign(\dot{\varphi}). \qquad (6)$$

Results of modeling are shown in Fig. 13 – 15.

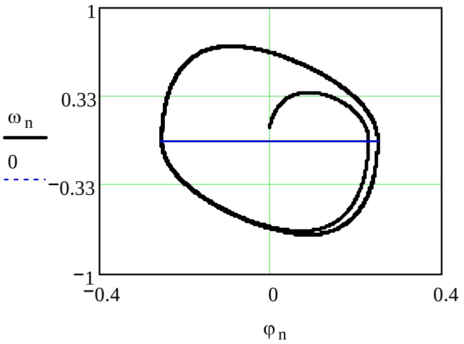

Fig. 13. Motion in phase plane for $M_0 \cdot sign(\dot{\varphi})$

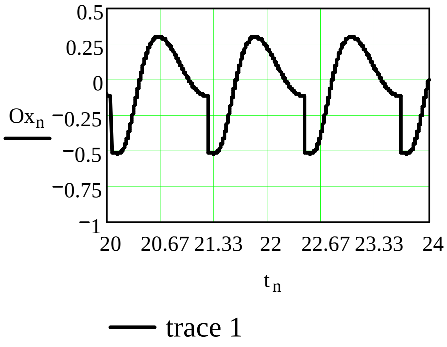

Fig. 14. Reaction Ox in time domain for $M_0 \cdot sign(\dot{\varphi})$

$$T_n := \sum_n Ox_n$$

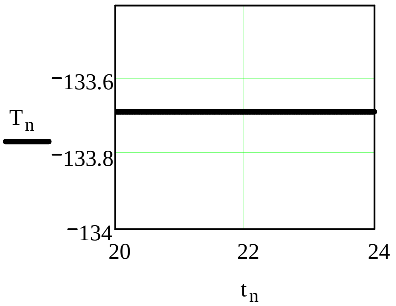

Fig. 15. Middle value of full impulse $M_0 \cdot sign(\dot{\varphi})$

As can be seen from Fig. 14, 15, full impulse is negative. It means that middle value of reaction in point O push hull to the right and this control may be used for robot actuators.

VII. CONCLUSION

The field of use of natural-shaped bodies and movers is yet little known to the researchers. Obviously the forms and drives adapted in the nature have taken thousands and millions of years to develop till the current state. Though, most probably this is not the final, nor most optimized possible body design. Field research has proven swimming efficiencies for biological fish as high as 95% [1.] in comparison to best robotic fish locomotion results so far have reached only 25% efficiency, that directly shows the potential growth of the subject. For sure research and development of such swimmers has a great future for applications needing relatively small bodies with a high mechanical efficiency in many fields.

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Guntis Kuļikovskis, Māris Ābele, Edgars Kovals, Igors Tipāns, Semjons Cifanskis, Maarja Krūsmā, Žan-Gai Fontains, Jānis Vība. Robota zivs astes kustības ierosme ar adaptīvu vadību

Šī darba mērķis ir izstrādāt mehānisko dizainu biometriskam zemūdens transportlīdzeklim ar adaptīvu vadību. Šī mērķa īstenošanai paredzēts izgatavot transportlīdzekļa vadības prototipus ar iespējami vienkāršiem dzinekļiem, kustības radīšanai lietojot vibrācijas ar adaptīvu vadību. Šo mehānisko dizainu pēc tam var lietot, lai sīkāk izpētītu kustību dažādās hidrodinamiskajās vidēs.

Biometriskie roboti savu uzbūvi aizguvuši no dzīvām radībām, piemēram, cilvēkiem vai insektiem. To spējas ir nokopētas no pasaules izcilākajiem veiksmes piemēriem - dzīviem organismiem. To izturēšanās neparedzamā pasaulē ir veiksmīgāka nekā laboratorijas vidē. Robotu inženieri ir spējīgi apvienot bioloģijas zinātnes ar skaitļošanas zinātnēm. Bioloģiskā izpēte mums sniedz padziļinātu izpratni par to, kā dzīvnieki izdzīvo. Piemēri - dziļo ūdeņu radību uztveres orgāni vai gekona gravitāciju pārvarošās kājas. Skaitļošanas ierīču ātrums, jauda un izmērs ļauj mums atveidot primitīvas neirofizioloģiskas smadzeņu aktivitātes. Apgrieztā inženierija (meklējot rezultātu caur procesu uz sākumu) pieņem, ka sākums eksistē. To, ka tas ir iespējams, pierāda fakts, ka ir dzīvnieks, kas spēj noteikt kustīgus objektus, lidojot bez redzama gaismas ķermeņa [1].

Pašlaik biometrisko zemūdens robotu izpēti sekmē nepieciešamība pēc efektīvākiem, elastīgākiem, manevrēt spējīgākiem, stabilākiem un piemēroties spējīgākiem objektiem, kas var sekmīgi funkcionēt bargos apstākļos. Galvenais dzenošais spēks ir tas, ka šodienas zemūdens transportlīdzekļi ir paredzēti atvērtiem un stabiliem ūdeņiem. Šie aparāti lieto dzenskrūves, lai iegūtu dzinējspēku, un tiem ir ļoti ierobežotas manevrētspējas. Biometriskie zemūdens transportlīdzekļi ir nepieciešami galvenokārt vidēs, kur ir vitāli nepieciešama laba manevrētspēja, efektīvs dzinējspēks daudzos virzienos un ātra reāllaika reakcija. Ātra vadība un augsta manevrētspēja kā arī samazināti izmēri tiek iegūti bez paaugstinātas sarežģītības pakāpes.

Piedāvātajam mehāniskajam dizaina modelim ir vienkārša modelēšana un vadība. Gadu laikā ir iegūta stingra zināšanu bāze par elastīgo auklu vibrācijām. Tas ļauj analizēt spuru aktuatoru kinemātiku un to vadību. Zivs vadība var tikt izteikta ar piemērotu ierosmes svārstību atrašanu, lai radītu vēlamos kustību musturus.

Гунтис Куликовскис, Марис Абеле, Эдгарс Ковалс, Игорс Типанс, Семен Цифанский, Маарья Круусмаа, Жан-Гай Фонтайн, Янис Виба. Возбуждение движения хвоста рыбы с адаптивным управлением

Суть этой работы - разработать механический дизайн с адаптивным управлением для биометрического подводного средства передвижения. Для реализации этой цели планируется изготовить прототипы транспортных средств в рамках возможности простыми движителями, используя вибрации с адаптивным управлением для создания движения.

Биометрические роботы свое строение усвоили от живых существ как люди или насекомые. Их способности скопированы из самых замечательных примеров удачи - живых организмов. Их поведение в непредвиденном мире более удачна, чем в среде лаборатории. Инженеры роботов способны объединить знания биологии и компьютеров. Биологические исследования дает нам углубленное понятие о том, как животные выживают, например, интересными являются органы восприятия глубинных животных или ноги гекона, превозмогающие гравитацию. Скорость, мощность и размер вычисляющих машин позволяет нам воспроизвести деятельность примитивного неврофизиологического мозга. Обратная инженерия (когда результат изыскивается через процесс на начало) принимает, что начало существует. При том, зная животное которое способно определить подвижные объекты без видимых светильников, это возможно [1].

Потребность в более эффективных, эластичных, маневровых, стабильных и приспособленных объектов, которые могли бы успешно функционировать в суровых условиях, способствует исследование биометрических роботов подводного движения. Главной движущей силой является то, что нынешние подводные агрегаты предусмотрены для работы в открытых и стабильных водах. Эти агрегаты используют винты для создания движения, и являются очень мало маневроспособными. В основном биометрические подводные транспортные средства необходимы в ситуациях, где эффективная движущая сила и быстрая реакция в реальном времени витально необходима. Быстрое управление и высокая маневроспособность усваивается без повышенной степени сложности.

Дополнительным качеством дизайна данной механической модели является простое моделирование и управление. За многие годы накапливались знания о вибрациях эластичных шнуров. Теперь это позволяет анализировать кинематику плавников и их управление. Тогда управление рыбы переносится на разыскивание подходящего режима колебаний, чтобы получить желаемые движения объекта.