

1 Original Research Article

2 **A DESIGN OF BUMP SENSOR MECHANISM**

3 **FOR ROBOTIC FISH**

4

5

6

7

8

9

10 **ABSTRACT**

Aims: This work aims at finding out the effectiveness of a commercial micro-switch as the base component for building bump sensor for a design of a robotic fish.

Methodology: A pair of micro switch (the type commonly used in computer mouse and similar devices) were assembled between the robot fish tip (actually a cone with the Mackerel fish profile) and the body, such that when the robot collides with a hard object, the switches will be depressed thus sending signal to its controller. The void between the switches were filled with collapsed polyurethane foam. The switches contact are continuously poled and the side that closes first is the side the robot is steered away from. False signals due to mechanical contact bounce was suppressed via software switch debounce algorithm. Test was focused on the debounce algorithm and the load to activate the switches. Furthermore, a modified IFD (compressive tests) on 1cm³ foam sample was performed.

Results: A spectrum analyzer sampling of the undebounced switches signal indicates the natural frequency of the vibration to be approximately 8.5kHz. Thus the controller will be sampling the switches contact at about 941.18 per second when operating at the design 8MIP (million instruction per second). The activation load test indicates that the minimum load to activate the left switch (3.42N) is less than that of the right (5.50N). The modified IFD test indicates that the force to compress the collapsed polyurethane foam by 50% is between 0.32N to 0.41N. A field test on the robot shows the robot respond well to the switch input as designed.

Conclusion: The bump sensor as used in this research performed as expected despite the problems associated with mechanical switches. The limiting factor to this design as implemented is the minimum speed to activate the switches. The hydrodynamic drag force (0.00128N) is much less than the 5.86N force required to activate the sensor at the calculated minimum speed of 0.096 m/s. The force required to activate the switches is high due to the water proof coating used for them. The idea of the minimum speed to activate the bump switch is to ensure a fail safe operation when deployed. This design can be used for dark cave and also for cloudy water and where so much debris exists. It can also be used to augment other navigational techniques.

11

12 Keywords: Underwater navigation, Robotic fish, Underwater sensor augmentation, Short

13 range-sensor

14

15

16 **1. INTRODUCTION**

17

18 Biological fishes and underwater creatures use a variety of methods to navigate and avoid

19 obstacles. Notably, they use their eyes, tentacles/whisker (*octopus vulgaris* and catfish),

20 sonar (dolphin), lateral lines, electric field (e.g. catfish, platypus) [1, 2, 3], Black ghost

21 knifefish (*Apteronotus albifrons*)[4]). In underwater vehicles, many researchers have focused

on the use of sonar system augmented with inertial guidance's system like gyroscope, example is the work of Robert et al. [5]. The other method that is receiving attentions is the use of lateral lines to perform the sensing by adapting different hydrodynamic force sensing methodology [6,7,8 9]. The use of tentacle is being adapted for close range navigation. Some researchers like Solberg et al., (2008) focuses their attention on electric field based navigation while others like Junaed et al., [10] worked on vision based navigational methodology.

In robotics, sonar systems are often used for ranging due to their low cost and small size [11]. The signal is sent out continuously or pulsed. The pulsed mode is used for eliminating frequent misreading caused by crosstalk or external sources operating nearby [12]. Sonar systems have been very attractive for underwater imagery being capable of longer range and are not affected by mucky or muddy water [13, 14]. High power ultrasonic systems have been known to negatively affect underwater ecosystem [15]. Also very powerful Low frequency and activated sonar (and mid-frequency sonar) have been claimed to also affect marine life [16].

According to Fernandez [8], the fish lateral line is a versatile short-range sensor organ. The lateral line was said to be used for "mapping environments [17], identifying objects [18, 19], tracking prey [6,7], and conserving energy while swimming in wakes" [20]. Various devices are being adapted to act as artificial neuromast – the main sensing organ in the lateral line. MEMS (microelectromechanical system) technology have being used for artificial lateral line[21, 22], while another researcher used hot-wire anemometry [4]. Strain gauges, piezo-resistive, and piezo-electric sensors have being tried also [23].

According to Solberg *et al.* [3], object location using weak electric fields by some aquatic creatures are almost a century old. Also "the principle of biological active electrolocation is that objects that differ in impedance from the surrounding medium distort the self-generated field, and arrays of sensors (electroreceptors) on the body detect these distortions." [3] Other researchers [1, 4, 24] indicated that changes as small as 0.1% can be sensed. To imitate this biological navigation methodology, Solberg *et al.* [3] installed ordinary electric conductor on their test robot and perform object detection in fresh and salt water in a premapped environment.

This work aims at finding out the effectiveness of a commercial micro-switch as the base component for building bump sensor for a design of a robotic fish. Cheaper and distributed but dependable robots have being hyped by the like of brooks and flynn [25] as the next direction in robotic research. This is more so when the goal is to build swam robots or community of robots.

This article is further divided into the following sections; materials and methodology used, the results obtained, discussion of the results, conclusions and recommendations. In the materials and method section, a description of the bump sensor is given and the potential problem with the design discussed immediately after it. The debounce problem associated with mechanical switches is then focused on in terms of the software solution, experimental tests and an experiment with a robotic fish in which the design was implemented. The effect of padding with collapsed foam and insulation with silicone (as implemented in the robotic fish) was documented and discussed.

2. MATERIALS AND METHODS

2.1 Description of the Bump Sensor

The bump sensor presented here uses a pair of micro-switches (Fig. 1a), soldered to a PCB board (1cm by 4cm) and placed on each side of the haul of a robotic fish (Fig. 1b). Thereafter, collapsed polyurethane foam is used for filling the spaces between them and to level up the assembly (Fig. 2a). The switches were then water proofed with automotive gasket seal silicone. The switch tip area (Fig. 2b) was filed down so as to reduce resistance to pressing when in operation. A nose cone is then attached to the haul as shown in Fig. 3. The switches were connected to a PIC18F4520 microcontroller using 3 cables. When there is collision with an object that cannot be detected by other means, the switches are closed and the rate of closure is measured by the microcontroller, this it use for determining whether to turn the robot to the left or right.

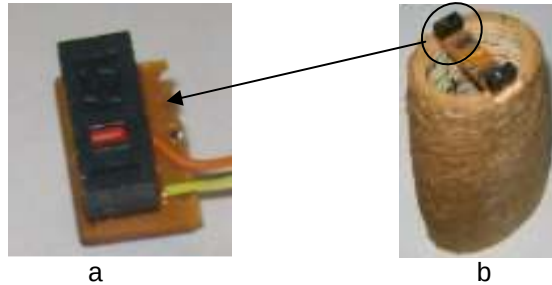


Fig. 1 (a) Micro switch (b) the micro switches are assembled on each side of the robot haul.

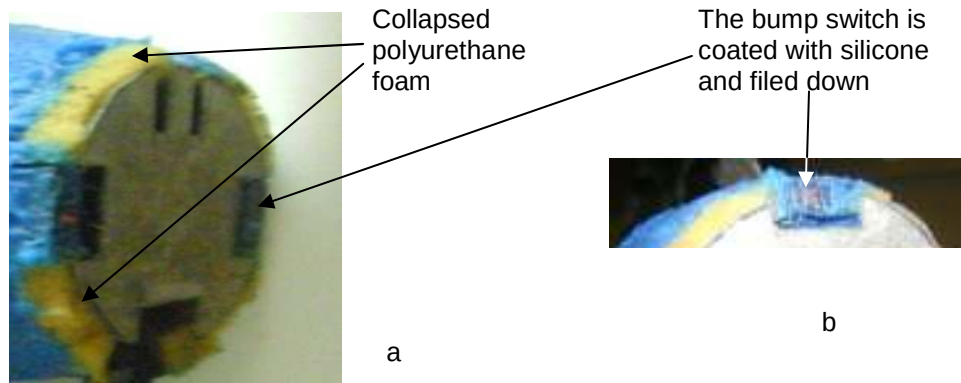


Fig. 2 (a) Collapsed polyurethane foam is used for filling the gaps. (b) The bump switches were waterproofed with silicone rubber and filed down to reduce resistance to depression.

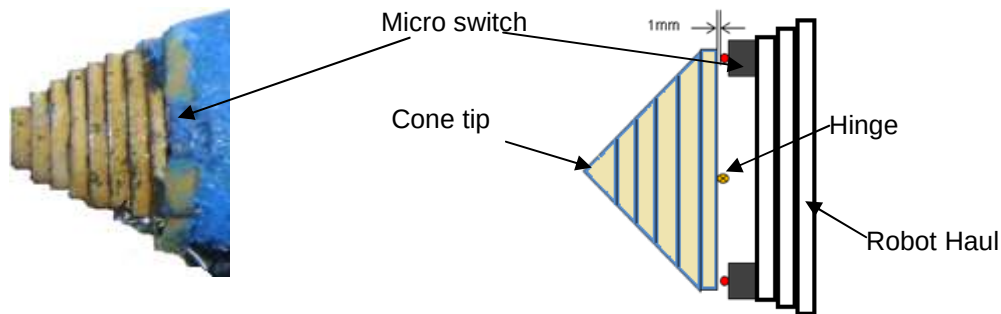


Fig. 3 Nose cone assembly of the robot

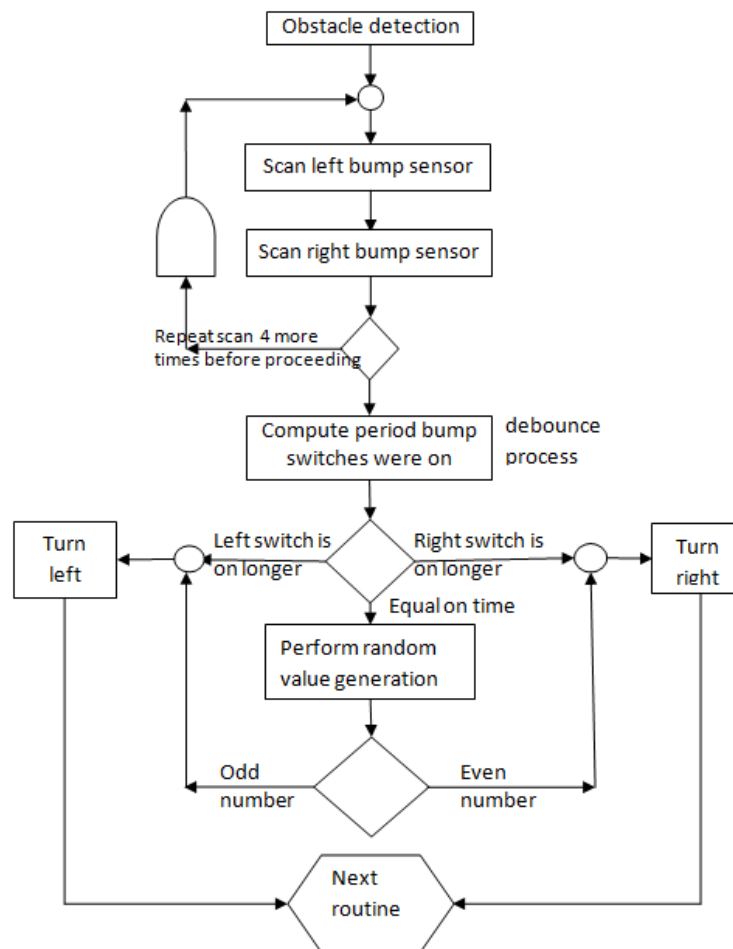
108
109
110
111
112
113
114
115
116
117
118
119
120
121
122
123
124

2.2 Potential Problems with the Design

There are two potential problems with this design; one is mechanical bouncing. The bump sensors are plain mechanical switches, therefore, there will be bouncing of their contact (the click noise). To the microcontroller running at 32MHz (or 8MIP for Microchip microcontrollers used for this work), a single click can be interpreted to mean millions of inputs. There is thus a need for debouncing, either in code or by introducing a damping device. The second option will make the assembly to be more bulky and perhaps unreliable. The other problem is uneven load between the two switches and the urethane backing such that a direct end on collision with obstacle may be misinterpreted as lopsided collusion.

2.3 Debounce Pseudo Code

Fig. 4 is the flow chart of the bump routine implementing the debounce routine code shown below with some useful comments. The code is implemented in assembly language.



125 Fig. 4 Flow chart for the bump switch based obstacle detection subroutine

126 Obstacle detection and avoidance pseudo code for Microchip PIC18F4520
127 ; -----

```

128 ; Check bump switch every 0.5 seconds
129 ; Check left, check right
130 ; use output 00,01,10, 11 to determine action
131 ; 00 = ignore
132 ; 01 = turn right => bumped on the left
133 ; 10 = turn left  => bumped on the right
134 ; 11 = turn random => head on collision
135 ; keep turning until bump read zero
136 ;Call routine after every 20ms
137 03AE 2A2D INCF 0x2d, F, ACCESS
138 03B0 A080 BTFSS 0xf80, 0, ACCESS
139 03B2 2A30 INCF 0x30, F, ACCESS
140 03B4 B080 BTFSC 0xf80, 0, ACCESS
141 03B6 0630 DECF 0x30, F, ACCESS
142 03B8 A280 BTFSS 0xf80, 0x1, ACCESS
143 03BA 2A2F INCF 0x2f, F, ACCESS
144 03BC B280 BTFSC 0xf80, 0x1, ACCESS
145 03BE 062F DECF 0x2f, F, ACCESS
146 03C0 9413 BCF 0x13, 0x2, ACCESS
147 ;Process result if already run 5 times=0.1s
148 03C2 0E05 MOVLW 0x5
149 03C4 602D CPFSLT 0x2d, ACCESS
150 03C6 D001 BRA 0x3ca
151 03C8 0012 RETURN
152 ;possible results
153 ; 00 = ignore
154 ; 01 = turn right => bumped on the left
155 ; 10 = turn left  => bumped on the right
156 ; 11 = turn random => head on collision, use some time base last
157 digit
158 03CA C032 MOVFF 0x32, 0xffa
159 03CC FFFA NOP
160 03CE 6A2D CLRF 0x2d, ACCESS
161 03D0 7613 BTG 0x13, 0x3, ACCESS
162 03D2 6A31 CLRF 0x31, ACCESS
163 ; if on it must be so at least 4x20ms=0.08s though checked for 0.1s
164 03D4 0E08 MOVLW 0x8
165 03D6 602F CPFSLT 0x2f, ACCESS
166 03D8 8231 BSF 0x31, 0x1, ACCESS
167 03DA 6030 CPFSLT 0x30, ACCESS
168 03DC 8431 BSF 0x31, 0x2, ACCESS
169 03DE 0E05 MOVLW 0x5
170 03E0 6E2F MOVWF 0x2f, ACCESS
171 03E2 6E30 MOVWF 0x30, ACCESS
172 03E4 9080 BCF 0xf80, 0, ACCESS
173 03E6 9280 BCF 0xf80, 0x1, ACCESS
174 03E8 5031 MOVF 0x31, W, ACCESS
175 03EA 26F9 ADDWF 0xff9, F, ACCESS
176 03EC 0012 RETURN 0 ; no collision
177 03EE D75E BRA 0x2ac ; Turn_Left2
178 03F0 D771 BRA 0x2d4 ; Turn_Right2
179 ; Random turn
180 03F2 A613 BTFSS 0x13, 0x3, ACCESS
181 03F4 0000 NOP

```

```

182      03F6      0000      NOP
183      03F8      0012      RETURN 0
184

```

185 In determining the parameters (such as timing) to be used for the code in the debounce
186 algorithm, a test is needed to be carried out on the switches so as to get parameters like
187 resonant frequency and frequency spectrum of the bouncing action using spectrum
188 analyzer. Also, there is need to know by how much the switch and the collapsed
189 polyurethane foam will skew signal received simultaneously by performing activation load
190 test.

191
192
193
194

195 2.4 The Switch Debounce Test

196

197 This test involves using a condenser microphone to capture the sound (the click) output of
198 the micro-switch when depressed. The frequency spectrum and time series value were
199 captured by the TFD scope 2.0 spectrum analyzer and oscilloscope.

200

201 2.5 The Activation Load Test

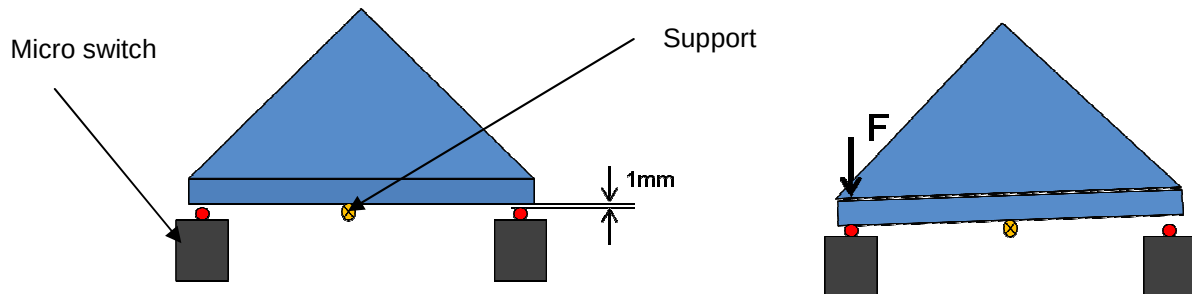
202

203 The activation load test involved finding out the minimum force to actually cause a response
204 (or to close the switch). The lower the force is, the likelihood of the switch closing when the
205 robot hits an object especially at slow speed. The micro switch requires a minimum of
206 0.015N to depress according to the manufacturer [26]. Equipment for the switch debounce
207 test includes CAMRY® load cell with digital output and 1cm³ sample of the collapsed
208 polyurethane foam used in between the haul and the cone. Using Fig. 5, the test was
209 performed by depressing the nose cone on one side with the load cell below it until a click of
210 the micro switch is heard. The load cell reading was then taken; both micro switches were
211 tested 5 times to get an average reading.

212

213 Five samples of 1cm³ polyurethane foams were also subjected to a compressive test by
214 putting them on the CAMRY® load cell and depressed to 50% of its original height. The
215 compressive test was performed for each side of the 1 cm³ foam sample. This is a
216 modification to Polyurethane Foam Association standard [27]. Polyurethane Foam
217 Association uses IFD (Indentation Force Deflection) table which is defined as the amount of
218 force, in pounds, required to indent a fifty square inch, round indenter foot into a predefined
219 foam specimen a certain percentage of the specimen's total thickness. This modification
220 allows the resistive force to compression to be determined.

221



222

223 Fig.5 Measuring the force required to activate the bump switch and the collapsed
224 polyurethane foam backing. F is the applied load until a click is heard.

225

226 **2.6 Experimental Verification**

227

228 To verify the debounce coding scheme cum obstacle detection algorithm, the following
229 equipments were used; Microchip MPLAB IDE (integrated development environment),
230 Microchip PICkit 2 (as debugger), TFD Scope 2.0 (as spectrum analyzer and oscilloscope).
231 The MPLAB IDE was started and switched to debug mode. Then, the PICkit 2 was
232 connected to the microcontroller and the computer hosting the MPLAB IDE. The nose cone
233 of the robot was pressed slowly and then fast to see if the program execution will branch
234 appropriately. Head on collision was simulated by pressing the cone at the tip firmly. The
235 program branching were observed throughout. Also a field test was performed on the robot
236 with the sensor mounted as shown in Figs. 1, 2 and 3. The robot was made to swim in a
237 small water tank (60.96cm x 121.92cm x 60.96cm wooden box) filled with water to a depth of
238 30cm or pressure head of 2.91kPa. (Fig.6). A digital camera - Sony Cyber-shot digital
239 camera (model DSC-S730) was set to VGA mode for recording the movements of the robot
240 as it swims.
241



242

243 Fig. 6 Wooden box for testing the robot bump sensor. The robot is made to swim inside it in
244 a tight circle
245

246

247 **3. RESULTS**

248

249 **3.1 The switch debounce test result**

250

251 The undebounced micro switch signal output is shown in Fig. 7, while Fig. 8 shows the
252 spectrum analyzer output of the micro switch.
253

254

254 **3.2 Switch activation load test result**

255

256 The force to cause each button to be activated is shown in Fig. 9. Furthermore, table 1
257 shows the mean and standard deviation of the minimum force to activate the left and right
258 micro-switches.
259

260

260 **3.3 Foam compressive test result**

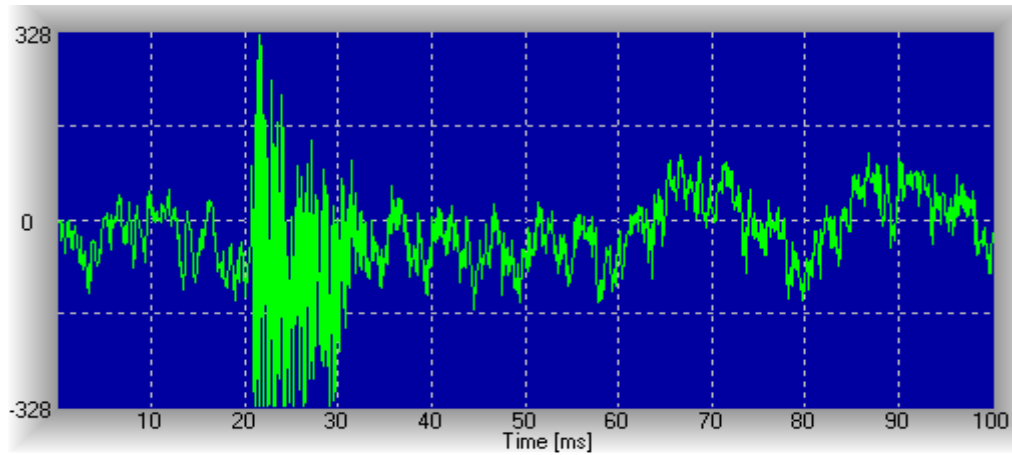
261

262 The result of the modified IFD test (compressive tests) on five samples of the 1 cm³
263 collapsed polyurethane foams is shown in Table 2 and Fig. 10.
264

3.4 Results of experimental verification

266

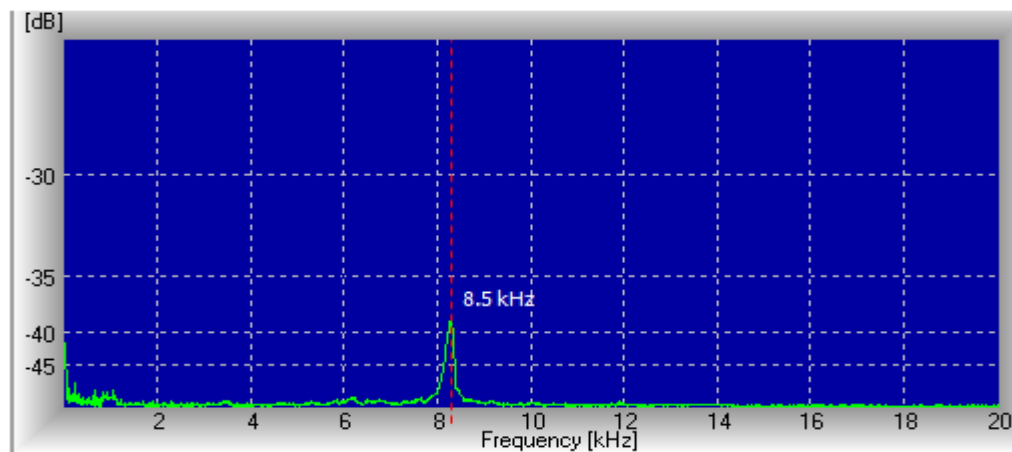
267 It was observed that the code branched as designed, for example, pressing the left switch
268 causes code for left turn to be executed. Field test result is shown as sequence of still
269 images of the robot (Fig. 11) making turn as it bumps into the wall of the pool.
270



271

272 Fig. 7 Oscilloscope displaying the undebounced micro switch signal output. Signals
273 between 20 and 30ms are artifact due to the 50Hz power line
274

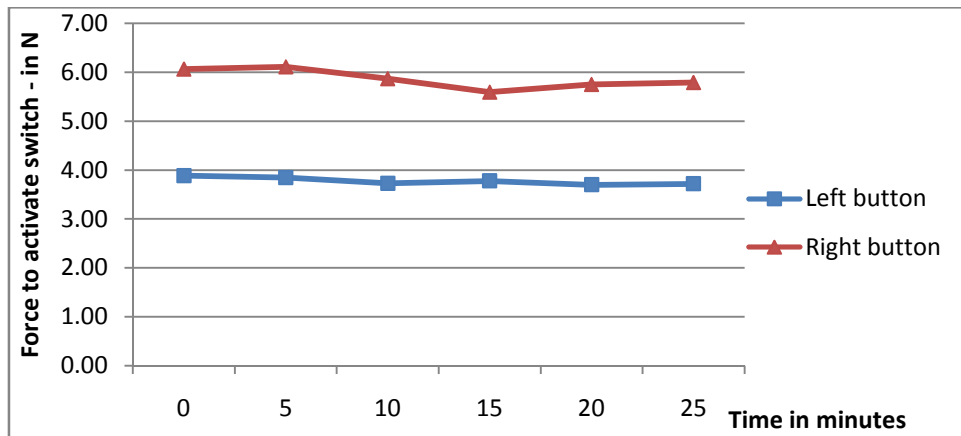
275



276

277 Fig. 8 Spectrum analyzer display of the undebounced micro switch signal output

278



279

280 Fig. 9 A plot of force to activate the left and right bump switch

281

282

Table 1. Mean and standard deviation of force (in N) to cause the left and right bump switch (micro switch) to be activated.

	Left button(N)	Right button(N)
Mean	3.78	5.86
Standard deviation	0.07	0.18

283

A dorsal view is implied in identifying the left and right switch

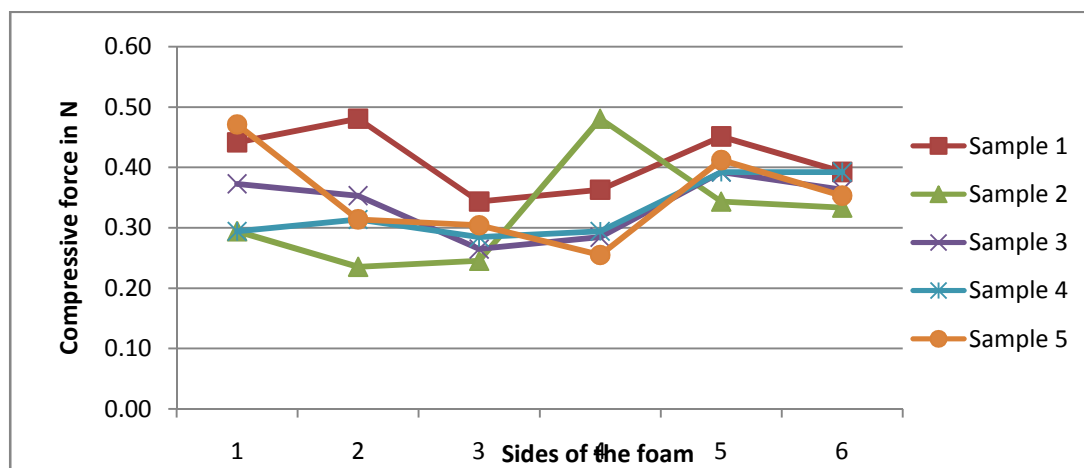
284

285

Table 2. The result of the modified IFD test (compressive tests) on five samples of the 1 cm³ collapsed polyurethane foams. Values are in Newton.

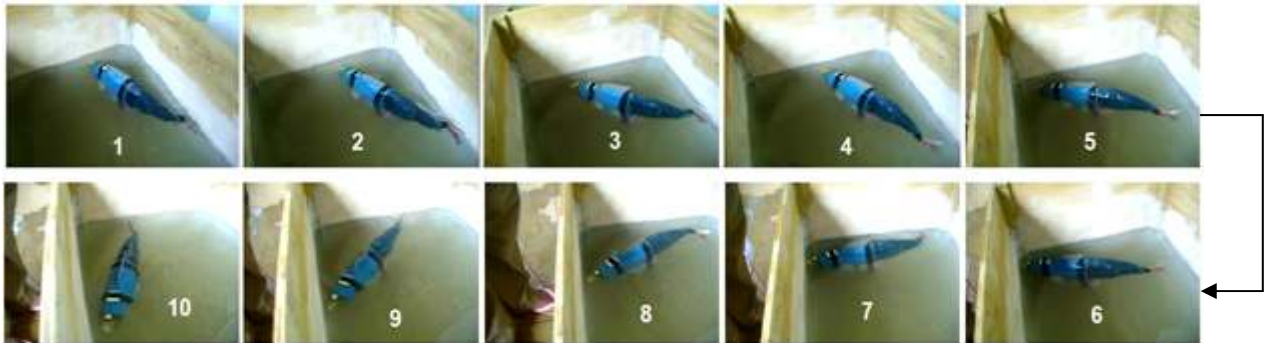
Foam sample					
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Mean	0.41	0.32	0.34	0.33	0.35
STD	0.05	0.08	0.05	0.05	0.07

286



287

288 Fig. 10 Modified IFD result – compressive force to cause 50% depression in the collapsed
 289 foam height.
 290



291 Fig. 11 Still images of the video of the swimming robot using the bump sensor to perform
 292 sharp turn in the box
 293

294 4. DISCUSSIONS

295 4.1 The Switch Debounce Test

296 This test aimed at removing false signal input to the microcontroller due to switch contact
 297 bounce. From the spectrum analyzer display (Fig. 8), the switch bounce frequency is at
 298 8.5kHz approximately. From this information we can deduce the number of inputs to the
 299 microcontroller as
 300

$$301 \quad = \frac{\text{Microcontroller MIP}}{\text{Switch bounce frequency}}$$

302 where

303 Microcontroller MIP = 8,000,000 (32MHz clock was used for this work)

304 Therefore, the number of inputs to the microcontroller is $8,000,000 / 8,500 = 941.18$ inputs per
 305 second, that is, one click of the switch will generate ≈ 941 inputs. In periodic notation, this is
 306 equal to

$$307 \quad T = 1/941.18 = 0.0010625 \text{ s} = 1,062.5\mu\text{s}$$

308 The microcontroller as designed will execute one instruction in $0.125\mu\text{s}$, it implies that it will
 309 always have to wait or idle for $T / 0.125$ instructions before deciding whether the switch
 310 contact was closed or opened and is given as

$$311 \quad 1,062.5\mu\text{s} / 0.125\mu\text{s} = 8,500 \text{ instructions}$$

312 or $(0x100)*(0x21)$ in hexadecimal notations.

313 Thus a delay or counting period must be set to $1,062.5\mu\text{s}$ or 8,500 instructions before
 314 deciding on if the switch was activated or not. In the debounce routine, the measurement is
 315 done 5 times with the delay set to the above value. Every 0.5s, the measurement is
 316 repeated.

321 4.2 Activation load test

322 From Table 1 and Fig. 8, the right button is stiffer, requiring 5.86N on average to activate it.
 323 This value is about 35% higher than the left button average activation force. From Table 2
 324 and Fig. 9 it can be seen that the force to cause 50% compression ranges between 0.24N to
 325 0.48N with the mean varying between 0.32 to 0.41. The standard deviation for three samples

is 0.5 meaning the other two are skewed perhaps due to assembly errors – such as the glue entering into the foam pores. According to the manufacturer datasheet, 0.015N is required to activate the micro switches. The 0.32N to 0.41N require for the foam is 21 to 27 times additional load required to depress the micro switch. Therefore, the actual force required to activate the switch is

$$\begin{aligned} (3.78-0.24) \text{ to } (3.78-0.48) &= 3.54\text{N to } 3.30\text{N or averagely } 3.42\text{N} \\ &\text{for the left bump micro-switch} \\ (5.86-0.24) \text{ or } (5.86-0.48) &= 5.62\text{N to } 5.38\text{N or averagely } 5.50\text{N} \\ &\text{for the right bump micro-switch} \end{aligned}$$

These high values (compared to 0.015N by the manufacturer of the micro switches) are due to the water proof coating with silicone and due to assembly errors – such as the glue entering into the foam pores.

The question that arises is that, at what minimum speed should the robotic fish be moving so as to activate the bump switches. If we work by the right bump switch that requires maximum force to depress it i.e. 5.86N and hydrodynamic forces are ignored, then from Newton's second law of motion, impulse is defined as

$$F \cdot t = mv_1 - mv_2$$

where F is force acting, t is period of action, m is mass of the body, v_1 is final velocity after impact and v_2 is initial velocity before impact. Also, the minimum speed will be just enough to bring the robot to a standstill, that is $v_1 = 0$.

If m = mass of the robot = 592g and
 F = the total force required to depress the switch = 5.86N, then
 $F \cdot t = mv_1 - mv_2 = 5.86 \cdot t = 0.592 \cdot 0 - 0.592 \cdot v_2$
or $5.86 = -0.592 \cdot v_2 / t$ negative implies a deceleration
 $v_2 / t = 0.592 / 5.86 = 0.096 \text{ m/s}^2$
and hence
 $v_2 = 0.096 \text{ m/s}$ over a period of 1s

This is the minimum speed to activate the micro-switches upon impact with an obstacle without hydrodynamic forces involved.

Now, fish swimming inside water will experience hydrodynamic forces D_v . The D_v will be additional load the fish robot had to overcome in order to successfully depress the switch upon impact with an object. If we assume the fish is coasting, that is, no wagging of tail, just sliding, then the standard drag equation (1) can be applied.

$$D_v = \frac{1}{2} \cdot C_d \cdot S_a \cdot V^2 \cdot \rho \quad (1)$$

V is the fish forward speed and ρ is water density (1000 kg/m^3), C_d is the drag coefficient which depends on the Reynolds number and is given as

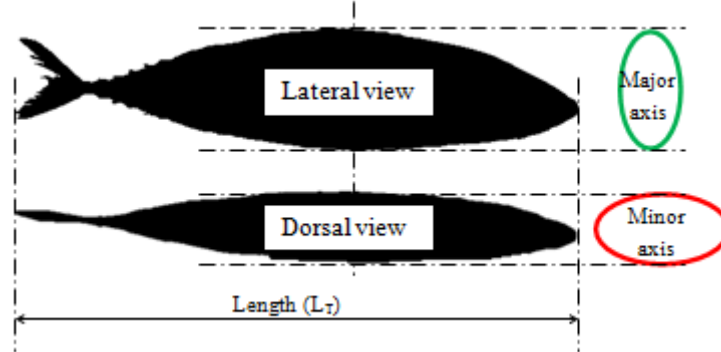
$$C_d = 1.328 \text{Re}^{-0.5} + 0.074 \text{Re}^{-0.2} \quad (2)$$

$$\text{Re} = L_T V / \nu \quad (3)$$

Thus, C_d is the sum of laminar and turbulent components of the coefficient of drag derived from Reynolds number (Re) [28, 29]. ν is the water kinematic viscosity ($1.12 \text{ mm}^2/\text{s}$) and L_T is the robot length (0.394m), see Fig. 10.

S_a is the frontal area with which it impact the water with. The maximum cross-section is used in this work. Thus,

379 $Sa = \pi \cdot a \cdot b = \pi * 0.0584\text{m} * 0.0915\text{m} = 0.017\text{m}^2$ where a and b are the minor and
 380 major axes of the maximum section of the robot fish as indicated in Fig. 10.



381 Fig. 10 The minor and major axes of the area as defined by the shape of the robot fish.
 382

383 Since $v_2 = 0.096\text{m/s}$ is the minimum speed to activate the micro-switches upon impact with
 384 an obstacle without hydrodynamic forces, then it must have also overcome the
 385 hydrodynamic forces D_v in order to maintain this minimum speed. Thus V (the forward speed
 386 of the fish) will determine the D_v experienced and is equal to v_2 or 0.096m/s . So from
 387 equation 1, 2 and 3 we have

388
 389 $Re = (0.394 * 0.096) / (1.12 * 10^{-6}) = 33,771$
 390 $Cd = 0.0072 + 0.0092 = 0.0164$ and
 391 $D_v = \frac{1}{2} * Cd * Sa * V^2 * \rho = \frac{1}{2} * 0.0164 * 0.017 * (0.096)^2 * 1000 = 0.00128 \text{ N}$
 392

393 5. CONCLUSIONS

394 The bump sensor as used in this work performed as expected despite the problems
 395 associated with mechanical switches. The limiting factor to this design as implemented is the
 396 minimum speed to activate the switches. The hydrodynamic drag force (0.00128N) is much
 397 less than the 5.86N force required to activate the sensor at the calculated minimum speed of
 398 0.096 m/s . The idea of the minimum speed to activate the bump switch is to ensure a fail
 399 safe operation when deployed. This design can be used for dark cave and also for cloudy
 400 water and where so much debris exists. It can also be used to augment other navigational
 401 techniques.

402 6. RECOMMENDATIONS

403 The design/implementation in this work requires that the robot collide with a moderately solid
 404 object, the micro-switches can be modified into whisker as in fresh water catfish or tentacles
 405 so as to increase the impact range. A much more computational mechanism for decision
 406 making will ultimately be required for such design than the one presented in this work.
 407

408

409 REFERENCES

- 410 1 MacIver, M. A., Sharabash, N. M., and Nelson, M. E. (2001). Prey-capture behavior
 411 in gymnotid electric fish: Motion analysis and effects of water conductivity. *Journal of*
 412 *Experimental Biology*, 204(3): 543–557.
 413 2 Nelson, M. E. and MacIver, M. A. (2006). Sensory acquisition in active sensing
 414 systems. *Journal of Comparative Physiology A*, 192(6): 573–586

415 3 Solberg J. R., Lynch K. M., and MacIver M. A. (2008). Active Electrolocation for
416 Underwater Target Localization. The International Journal of Robotics Research.
417 Vol. 27, No. 5, May 2008, pp. 529–548. DOI: 10.1177/0278364908090538

418 4 Nora M., Stefan S., Kolja K., Sandra H., Yimin N., Jan-Moritz P. F., J. Leo van H.
419 (2009). Design of a Lateral-Line Sensor for an Autonomous Underwater Vehicle.
420 Proceedings of the 8th IFAC International Conference on Manoeuvring and Control
421 of Marine Craft September 16-18, 2009, Guarujá (SP), Brazil. pp 292-297

422 5 Robert S., Andy F. and Penny P. (1999). A Sensor System for the Navigation of an
423 Underwater Vehicle. The International Journal of Robotics Research Vol. 18, No. 7,
424 July 1999, pp. 697-710.

425 6 Coombs S. and Fay R.R. (1993). Dipole source localization by mottled sculpin,
426 *Cottus bairdi*. Journal of the Acoustical Society of America, 93:2116-2123, 1993.

427 7 Coombs S. and Patton P. (2009). Lateral line stimulation patterns and prey orienting
428 behavior in the lake michigan mottled sculpin (*Cottus bairdi*). Journal of Comparative
429 Physiology A: Neuroethology, Sensory, Neural, and Behavioral Physiology, 195(3):
430 279-297, 2009.

431 8 Fernandez V., (2011). Performance Analysis for lateral-line-inspired Sensor Arrays.
432 PhD thesis, Massachusetts Institute of Technology

433 9 Roberto V., Otari A., Francesco V., Jaas J., Lily D. C., Gert T., Jennifer B., Maarja K.,
434 William M. M. and Paolo F. (2012). Hydrodynamic pressure sensing with an artificial
435 lateral line in steady and unsteady flows. Bioinspiration & Biomimetics. vol 7, No 3.
436 doi:10.1088/1748-3182/7/3/036004.

437 10 Junaed S., Philippe G. and Gregory D. (2009). Sensor-based Behavior Control for
438 an Autonomous Underwater Vehicle. The International Journal of Robotics
439 Research. Vol. 28, No. 6, June 2009, pp. 701–713. DOI:
440 10.1177/0278364908098560

441 11 Afolayan M.O. (2010). Potential of Watch Buzzer as Underwater Navigation Device
442 in Shallow Water Streams. Research Journal of Applied Sciences, Engineering and
443 Technology 2(5): 436-446, 2010

444 12 Tetsuji K., Kenji N., Yuuki K., and Takahiko Y. (2008). Application of Digital Polarity
445 Correlators in a Sonar Ranging System Electronics and Communications in Japan,
446 Vol. 91, No. 4, 2008. Translated from Denki Gakkai Ronbunshi, Vol. 127-C, No. 3,
447 March 2007, pp. 317–323.

448 13 Dura E., Bell J. and Lane D. (2004). Reconstruction of textured seafloors from side-
449 scan sonar images. IEEE Proc.-Radar Sonar Navig., Vol. 151, No. 2, April 2004

450 14 Capus C.G. Banks A.C. Coiras E. Tena Ruiz I., Smith C.J. and Petillot Y.R. (2008).
451 Data correction for visualisation and classification of sidescan SONAR imagery. IET
452 Radar Sonar Navig., 2008, Vol. 2, No. 3, pp. 155–169/155

453 15 Pierce B. (2008). Protecting Whales from Dangerous Sonar. [http://www.nrdc.org](http://www.nrdc.org/wildlife/marine/sonar.asp)
454 /wildlife/marine/sonar.asp (accessed April 21, 2010).

455 17 Teyke T. (1989). Learning and remembering the environment in the blind cave fish
456 *Aplocheilichthys jordani*. Journal of Comparative Physiology A: Neuroethology, Sensory,
457 Neural, and Behavioral Physiology, 164(5):655-662, 1989.

458 18 Weissert R. and von Campenhausen C. (1981). Discrimination between stationary
459 objects by the blind cave fish *Aplocheilichthys jordani* (Characidae). Journal of
460 Comparative Physiology A, 143:375-381, 1981.

461 19 Teyke T. (1985). Collision with and avoidance of obstacles by blind cave fish
462 *Aplocheilichthys jordani* (Characidae). Journal of Comparative Physiology A, 157:837-
463 843, 1985.

464 20 Liao J.C. (2006). The role of the lateral line and vision on body kinematic and
465 hydrodynamic preference of rainbow trout in turbulent flow. Journal of experimental
466 Biology, 209(20):4077-4090, 2006.

467 21 Yang Y., Nguyen N., Chen N., Lockwood M., Tucker C., Hu H., Bleckmann H., Liu C.
468 and Jones D.L. (2010). Artificial lateral line with biomimetic neuromasts to emulate
469 fish sensing. *Bioinspiration Biomimetic*. 2010 Mar; 5(1):16001. doi: 10.1088/1748-
470 3182/5/1/016001.

471 22 Zhi-guo Z. and Zhi-wen L. (2008). Biomimetic Cilia Based on MEMS Technology.
472 *Journal of Bionic Engineering* 5 (2008) 358–365

473 23 Hou S.M., Fernandez V., Lang J., Hover F., Triantafyllou M., Wee T.C., Ting X., Xu
474 J., and Jianmin M. (2013). Touch at a distance I: The development and fabrication of
475 bio-inspired pressure sensor arrays for ocean applications. Available online at
476 <http://censam.mit.edu/news/posters/2010/mt/1.pdf>. accessed on 26 July, 2013;
477 16:31 GMT

478 24 Nelson, M. E. and MacIver, M. A. (1999). Prey capture in the weakly electric fish
479 *Apteronotus albifrons*: Sensory acquisition strategies and electrosensory
480 consequences. *Journal of Experimental Biology*, 202(10): 1195–1203.

481 25 Brooks, R. A. and Flynn, A. M. (1989). Fast, Cheap and Out of Control: A Robot
482 Invasion of the Solar System. *Journal of The British Interplanetary Society*, 42: 478-
483 485

484 26 www.ck-components.com

485 27 PFA, (1994). Polyurethane Foam Association standard. Available online at
486 <http://www.pfa.org>

487 28 Jindong, L. and Huosheng, H. (2004). Building a 3D Simulator for Autonomous
488 Navigation of Robotic Fishes. *Proceedings of 2004 IEEE/RSJ International*
489 *Conference on Intelligent Robots and Systems. September 28-October 2, 2004,*
490 *Sendai, Japan.* pp 613- 618

491 29 Korkmaz D., Ozmen K.G., and Akpolat Z.H., (2011). Robust Forward Speed Control
492 of a Robotic Fish. 6th International Advanced Technologies Symposium (IATS'11),
493 16-18 May 2011, Elazig, Turkey pp 33-38.

494