Developing the Croatian Underwater Robotics Research Potential

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Abstract: This paper proceeds to lay out the activities being performed by the Croatian group of researchers from University of Zagreb, Faculty of Electrical Engineering and Computing, Department of Control and Computer Engineering, Laboratory for Underwater Systems and Technologies (LABUST), after having successfully applied to the REGPOT-2008-1 call and having been awarded a capacity-building grant for the "Developing the Croatian Underwater Robotics Research Potential – CURE" project. The scientific contributions to the state of the art of underwater and marine system technology of LABUST, based on which the capacity to further and intensify research activity is being built within the CURE project, fall mainly into three categories:

(1) unmanned small vessel modeling and identification, cf. Miskovic *et al.* (2009a,b,c).
(2) distributed coordinated and cooperative control, cf. Barisic *at al.* (2008, 2009a,c).
(3) embedded control systems engineering and software design, cf. Barisic *et al.* (2009b,d).

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1. INTRODUCTION

The regional potential programme of calls was instituted based on the CEC Com (1998, 2001), EURAB (2005). The policy foundation for the promulgation of this financing line to identified high-potential research institutions in the incubation phase can be found in the quote in EURAB (2005):

"*The capacity of Europe's regions to undertake research and innovation is a crucial factor in delivering the Lisbon Agenda. The challenge facing the Union is to unlock regional potential wherever it might be located and to harness this to support economic growth and the creation of employment.*"

The paper will present an overview of the project, only short-listing the research advances in a congested format. The interested reader is invited to further explore the scientific merit in the references and on the LABUST's website, *http://labust.fer.hr*, the project website *http://cure.fer.hr* and the Croatian national academic publication database web-site *http://bib.irb.hr*.

The paper describes the application of LABUST scientific-managerial thinking. The classification of activities is based on a road-map harmonizing the research already performed, research currently under way and envisaged research based on the implications reached thus far, with the intention of pursuing R&D goals in line with the Lisbon Agenda. This classification, funded by the CURE project is:

(1) transfer of know-how from internationally recognized groups to LABUST personnel,
(2) hiring on of certain profiles of experts into LABUST,
(3) scientific and professional maturation of others already on board at the time of grant award.

One of the characteristics of the research performed at LABUST following the above roadmap is fostering to job creation. This is achieved by the incubation and growth of the scientific ideas within the CURE project to the level of maturity allowing for commercial spin-off. Another characteristic is the social responsibility of research performed and use of potential technologies emanating from the project. The guiding principle is the mitigation of risk undertaken by humans by leveraging unmanned systems in the activities of first responding, salvage, rescue and containment, as well as law enforcement, monitoring and security in a variety of marine environments and theaters (surface, sub-sea).

The paper provides a layout of the CURE project activities in terms of *work-packages*, in Section 2. Section 3 lists technology research platforms and sensors procured in order to further LABUST's capacity to undertake application-oriented research and experimentation at sea. Section 4 covers activities aimed at increasing the volume and intensity of professional and research networking of LABUST, in the role of a highly competent regional center of excellence. Section 5 provides an overview of on-going research in the traditional topics of LABUST's competence.

2. PROJECT WORK-PACKAGES

As covered in the Introduction, CURE project is intended to elevate the Laboratory for Underwater Systems and Technologies to the level of an instantly recognizable, internationally visible R&D institution of twin, complementary and synergistic nature:

(1) A regional center of excellence in applied research and technical development of marine systems with a methodology of research that lends itself easily to commercial spin-off.

LABUST will use the CURE project to further differentiate its competence and foster growth of genuinely innovative ideas. The research areas of focus are: unmanned small vessel modeling and identification, distributed coordinated and cooperative control and embedded control systems engineering complemented by software engineering and design of hard-real time control applications.

(2) An instantly visible regional hub and contact point for the region. LABUST aims to articulate and facilitate world-wide consortium-building efforts directed at the region.

LABUST is dedicating a large degree of effort in executing specific tasks within the CURE to strengthen its international visibility. Procurement of challenging new platforms assures that LABUST has viable and attractive resources to commit to future research projects. The intention is for LABUST to be viewed as a "turn-key solution" to international research actors or consortium builders when questing for regional partners. The region aimed at is Western Balkans and Central – Eastern Europe, traditionally not on the scopes of the most active researchers in marine systems.

These goals are being pursued through the following work-packages:

(1) Procurement

LABUST has used CURE funding to procure off-the-shelf technology demonstrators and platforms. The key was the concept of an open architecture allowing future networking or augmentation with inhouse embedded control systems. The procurement was based around the practice of engineering and technical information-heavy communication with the prospective companies. It was critical for the company to signify its openness towards LABUST's intention of upgrading, augmenting or modifying embedded control, sensing and sensor-processing systems on board their marketed vessels.

(2) Employment

CURE has provided the funds to employ experienced researchers with varied background. Another potential well of employees was found among professionals with experience in industries and professions that are market drivers for innovative marine systems. The intention of such employment was to vary the methodology of research being pursued within LABUST and redefine strategies of system development. The commercial and industrial experience of such employees is needed to offset and complement the academic "ivory tower" wherein most pre-CURE LABUST researchers effected their research. Such an offset would help to overcome hurdles in spinning off ventures, patenting, marketing intellectual property or collaborating in technical projects with industry.

(3) S&T networking and fostering of international research activity

As covered in item 2 above, LABUST is committed to networking with regional and international research institutions. This is facilitated by an incubation of trust, collaboration and shared personal experience in experimental activities, leading to future formation of research consortia and joint application to funding calls. To do so, the CURE project has a dedicated work-package which includes the following activities: research internships / secondments / visits of LABUST research staff to competitive marine systems research institutions, a stipend for visiting experts for a short, concentrated stay and a period of collaboration with LABUST, a study tour of LABUST managers to explore and transplant research and business models and methodologies, and a programme of international interdisciplinary field training of marine robotics and applications.

(4) Dissemination

One of the goals is to form a strong "brand awareness" of LABUST's research results in the international marine systems research community. The intention is for the dissemination of results to clearly demarcate the areas and topics where excellence has been achieved and is continually being pursued further. CURE has allowed for the continuation and intensification of applied research efforts, as well as an increase in publishing activity.

(5) Management

The management, internal control, self-evaluation, archiving, book-keeping and accounting are all necessary preconditions for the achievement of project goals, lumped together in this work-package.

3. PROCUREMENT OF R&D EQUIPMENT

The methodology described in item 1 in the previous Section was a guiding principle in determining the procurement approach of the CURE project. However, this primary concern was only one out of a mix of concerns, extending to the economy of the purchase, maintenance and warranty support, level of documentation, existing research community and user knowledge-base. When combined, these considerations led to the procurement of the following items.

3.1 The Autonomous Underwater Vehicle

The OceanServer Technology Inc. of MA, USA's *Iver 2 autonomous underwater vehicle* contains two Intel Atom micro-ATX boards with 16 serial ports and two UTP 8P8C Ethernet ports each. The vehicle is equipped with a side-scanning sonar, a set of triaxial gyro-compasses, a magnetic compass and a 10-beam YSI combined DVL/ADCP [1] which utilized the 500kHz frequency for five

[1] Acoustic Doppler current profiler.

bottom-locking heads and the 1.0MHz frequency for the water-profiling, upward-facing heads. The working height-over-bottom range for the lower heads is 0.06 – 80.0m, the internal sampling rate of the YSI proprietary subsystem is up to 70 Hz, the accuracy is 0.002 m/s and the resolution 0.001 m/s. The drive for the main propeller is a brushless DC motor and the drives for the elevator and the rudder are steppers. The vehicle has a GPS antenna and an IEEE-802.11b/g antenna in the mast for use on the surface. The vehicle's top speed is 3.5kts and the dive floor is 90m. Endurance is 6h at average cruising speed of 2.5kts. The total system weight is about 25kgs, making it a three-man portable system.

3.2 The Remotely Operated Vehicle

The Seamor Marine of BC, Canada's *D300 remotely operated vehicle* is driven by 4 150W brushless motor-powered thrusters. Two are used for forward propulsion and the other two for submerging-surfacing. The latter are mounted vertically amidships, at a slight angular offset.

The vehicle is equipped with a 450m tether containing a 300VDC power pair, two RS-485 pairs, and 4 optical fibers. Fiber 1 is de-multiplexed into a composite video signal, an RS-485, and two RS-232 lines. Fiber 2 is terminated with an Ethernet hub opto-converter providing two UTP 8P8C 10Mbit/s Ethernet ports. The remaining two fibers are spare.

The main junction box transforms the incoming 300VDC into 48, 24 and 12VDC. A micro-controller inside the box routes the control commands received through the RS-485 pair wired down from the surface through the tether to four thrusters along with a 48VDC power supply. Other normally dummy-plugged wet-mateable whips feeding out of the junction box are: A PoE[2] with 48VDC power intended for the look-ahead sonar; An RS-232 plus a 24VDC pair intended for the DVL; An RS-232 plus a 24VDC intended for the SBL; An RS-485 plus a 24VDC intended for the USBL/modem.

The vehicle has a dive floor of 300m, and the top speed in surge of 3kts. The total system weight inclusive of the tether drum and the operator console is ca. 35kg, making it a three-man portable system.

3.3 The Look-Ahead Multi-Beam Imaging Sonar

BlueView Technologies of USA's *DF900-2250* look-ahead multi-beam imaging sonar features two transducer heads, one operating at 900kHz and the other operating at 2.25MHz. It is powered by a 48VDC source and is connected by a proprietary wet-mateable PoE port. A cable terminated on the user side by a standard UTP 8P8C Ethernet jack is provided by the manufacturer. Usable ranges are ca. 50m for the 900kHz head, with the range resolution of 1in, and ca. 5m for the 2.25MHz, with the range resolution of 0.4in. The pressure housing is tested to 330m.

[2] Power-over-Ethernet.

3.4 The Doppler Velocity Logger

The LinkQuest of USA's *NavQuest 600 Micro DVL* instrument was purchased to allow the ROV to directly measure speed-over-ground. This Doppler velocity logger operates four beams at 600kHz, requires 24VDC of power and is connected by an RS-232 serial COM port wired to a micro-series 8-pin Seacon wet-mateable connector. The working height-over-bottom range is 0.3 – 110.0m and the accuracy is 1% slant-range ±1mm. The pressure housing is tested to 6000m depth.

3.5 Modems

A pair of LinkQuest of USA's *SoundLink UWM 2000* modems was obtained. Each requires 24VDC of power, operates in the 26.77–44.62kHz at the top rate of 17800 bauds (symbols/s) and can be used to transfer up to 6600bit/s of payload data. Bandwidth is dependent on range. Maximum range is 1.5km. The pressure housing is tested to 2000m depth.

3.6 Ultra-Short Base-Line Localization System

The system obtained is the *MicronNav USBL* transducer with processor top-box and 2 *Micron DST* USBL transponders. Each transponder is capable of functioning as a very low bandwidth modem. The surface transducer is powered via the top-box connected to the mains. The top-box data connection has UTP 8P8C standard Ethernet, D-sub 9 pin female RS-232 serial COM or USB data-feed options. A diver strap-down 24VDC battery has been obtained allowing for one of the units to be mounted on the Iver 2 AUV. The other unit gets power (and data, if required to function as a modem) by an RS-485 plus 24VDC lead fed out of the ROV's junction box as described above. Both can function simultaneously, allowing for tracking the ROV's and AUV's positions in the same mission, in the same water-space. The transponders are neutrally buoyant in fresh water, weigh ca. 0.4kg in air, and are pressure-tested to 750m. The system can track horizontally in a 500m radius and vertically down to 150m depth, with the azimuth-elevation angular accuracy of $\pm 3°$ and range accuracy of 0.2m. In terms of percent-of-slant-range the $6°$ cone aperture produces an average error of $\tan\frac{6°}{2} = \tan 3° = 5.3\%$ of slant range.

3.7 Conductivity-Temperature-Density Probe

An Applied Microsystems *Minos CTD* instrument is used to measure the CTD profile of the water-column in order to calibrate sonars, the USBL system or modems to a more exact approximation of the speed of sound in water. The instrument is accessed by an RS-232 serial COM-port tied in with a 24VDC lead for battery recharging through a standard micro-series Seacon 8-pin female bulkhead mount. It has a battery life of 30h. The instrument's hull has been pressure-tested to 500m. The conductivity accuracy is ±0.01mS/cm and the temperature accuracy is 0.005C°.

3.8 Fluorometry Sonde

The *C6 Multi-Sensor Platform* fluorometry sonde can support, aggregate and log measurements of up to 6 simultaneously measuring *Cyclops* probes. The 6 probes, mounted on the instrument via micro-series wet-mateable Seacon 8-pin bulkhead mounts, measure chlorophyll, rhodamine, phycoerythrin, CDOM [3], crude oil and turbidity. The instrument is accessible by an RS-232 serial COM-port available through a micro-series Seacon 8-pin female bulkhead mount on the side opposite the Cyclops probes. The battery life of the instrument is 30h, the storage capacity is ca. 120.000 lines (about 30Mb) and the hull of the instrument has been pressure-tested to 600m. Maximum sampling time is 1s.

4. S&T NETWORKING AND FOSTERING OF INTERNATIONAL RESEARCH ACTIVITY

Section 2, item 2, has taxonomically listed the activities undertaken to further LABUST's involvement in networks of excellence in research, development, scientific exploration, and fielding of technology beyond state-of-the-art. Following the layout of Sec. 2 item 2 more detail is given below to the activities among the ones listed that have already been performed.

4.1 Research Internships / Secondments For LABUST Research Personnel

The internships representative of the partly of wholly by the CURE project are listed below:

(1) Mr. Matko Barisic spent 18.9.2008 – 23.12.2008 at Naval Postgraduate School, Monterey, CA 19340, USA. The secondment was spent under mentorship of prof. Anthony D. Healey, studying the application of virtual potentials and decentralized control functions to guidance of swarms of AUVs.
(2) Mr. Nikola Miskovic spent 1.1.2009 – 1.4.2009 at Consiglio Nazionale delle Richerce - ISSIA, Via de Marini 6, Genoa, Italy. The secondment was spent under mentorship of Mr. Massimo Caccia, applying the I-SO [4] method to identifying a non-linear and a linear model of the Charlie autonomous catamaran, cf. Miskovic *et. al* (2009c).
(3) Mr. Gyula Nagy spent 27.7.2009 – 26.10.2009 at the NATO Undersea Research Centre, Viale St. Bartolomeo 400, La Spezia, Italy. The secondment was spent under mentorship of dr. Vladimir Djapic, designing and implementing a back-stepping algorithm and a Kalman filter for path- and orbit-following control of a RIB USV circling around potential mine threats.

4.2 Programme Of International Interdisciplinary Field Training

This measure was undertaken to increase the level of overall research activity in marine systems in the region, as well as to steer this newly developed activity towards immediate applications in order to foster to job creation and encourage development of the region in line with the Lisbon Agenda.

The First Interdisciplinary Field Training in Marine Robotics "*Breaking the Surface 2009*", October 4 - 11, 2009, was carried out with assistance from the CUST [5], Argonauta [6], and Bius [7] NGOs. The venue was the island of Murter, and the field-work activities themselves took place within the National Park of Kornati. The field-work consisted of combined operations of professional and scientific divers and unmanned marine systems – AUVs and ROVs, complemented by sensors described in Sec. 3. The programme incorporated three programme tracks: Marine Robotics; Marine Biology; Maritime Archaeology. A total of 65 people took part, of which 20 student participants. Noted international lecturers and mentors came from the University of Limerick, Ireland, Centre Nazionale delle Richerce-ISSIA, Genoa, Italy, Polytechnic University of Marche, Ancona, Italy, University of Girona, Catalonia, Spain, NATO Undersea Research Centre, La Spezia, Italy, Hydroid LLC, USA, Bulgarian Academy of Sciences, Sophia, Bulgaria, ISPRA, Italy, University of Malta, la Valetta, Malta, and Harpha-Sea LLC, Kopar, Slovenia.

The past International Interdisciplinary Field Training is described in more detail at *http://bts.fer.hr/Bts2009.*

5. IN-HOUSE R&D ACTIVITIES

The primary research competence of LABUST lies in three areas: vessel dynamics modeling and identification; Distributed cooperative and coordinated control of unmanned vessels; And embedded control system engineering. This Section will give a short guide to facilitate understanding of LABUST's referred publications on the first two topics.

5.1 Vessel Dynamics Modeling And Identification

LABUST researchers have developed a procedure for the identification of linear or non-linear parameters of a large class of vessel models. The basic idea is the use of a *symmetric two-state relay with hysteresis* to induce self-oscillations. For the case of a *general SISO linear system, without prejudice to it being either static or astatic*:

$$G_P(s) = \frac{\sum_{i=0}^{m} b_i s^i}{\sum_{i=0}^{n} a_i s^i}, \quad m \le n$$

For which all the coefficients $\{a_i\}, \{b_i\}$ are unknown, $\varepsilon = \lceil \frac{n+m+1}{2} \rceil$ distinct experiments are required. Concatenation of measurements from all ε experiments yields: $\omega = [\,\omega_1 \,\cdots\, \omega_\varepsilon\,]^{\mathrm{T}}$, $\mathbf{P} = [\,P_1 \,\cdots\, P_\varepsilon\,]^{\mathrm{T}}$ and $\mathbf{Q} = [\,Q_1 \,\cdots\, Q_\varepsilon\,]^{\mathrm{T}}$. Here ω_j are the frequencies of the self-oscillations, and (P_j, Q_j) the real and imaginary parts of the relay's describing function, which can be looked up in Miskovic *et. al* (2009c), among other sources [8]. The block-matrix

[3] Coloured dissolved organic matter.

[4] Identification by use of self-oscillations.

[5] Center for Underwater Systems and Technologies.

[6] Association for Conservation and Sustainable Island Development "Argonauta".

[7] the Student Association for Biology Research of the University of Zagreb.

[8] In the referred sources, usually $\pm C$ is the output of the relay in on and off state, respectively, and $\pm x_a$ the switch-off, and switch-on, respectively, thresholds of the relay input.

algebra in $(1-3)$ identifies the parameters $\{a_i\}, \{b_i\}$. The notation below uses: $\mathbf{I}_\varepsilon = \mathbf{I}_{\varepsilon\times\varepsilon}$, $\mathbf{0}_\varepsilon = \mathbf{0}_{\varepsilon\times\varepsilon}$, $\underline{0} = \mathbf{0}_{\varepsilon\times 1}$, $\underline{I} = \mathbf{I}_{\varepsilon\times 1}$, $\mathbf{\Theta} = \begin{bmatrix}\mathbf{\Theta}_a & \mathbf{\Theta}_b\end{bmatrix}^T = \begin{bmatrix} a_1 & \cdots & a_n & b_0 & \cdots & b_m\end{bmatrix}^{\mathrm{T}}$. The dot-power symbol, $\cdot^k$, denotes the element-wise exponent.

$$\underbrace{\begin{bmatrix}\mathbf{\Omega}_a & \mathbf{\Omega}_b\end{bmatrix}}_{\mathbf{\Omega}} \mathbf{\Theta} = \underbrace{\begin{bmatrix} -\underline{I} \\ \underline{0} \end{bmatrix}}_{\mathbf{Y}} \tag{1}$$

$$\mathbf{\Omega}_a = \begin{bmatrix} \mathbf{0}_\varepsilon & -\mathbf{I}_\varepsilon & \mathbf{0}_\varepsilon & \mathbf{I}_\varepsilon \\ \mathbf{I}_\varepsilon & \mathbf{0}_\varepsilon & -\mathbf{I}_\varepsilon & \mathbf{0}_\varepsilon \end{bmatrix} \underbrace{\begin{bmatrix} \omega.^1 & \underline{0} & \underline{0} & \underline{0} & \omega.^5 & \underline{0} & \cdots \\ \underline{0} & \omega.^2 & \underline{0} & \underline{0} & \underline{0} & \omega.^6 & \cdots \\ \underline{0} & \underline{0} & \omega.^3 & \underline{0} & \underline{0} & \underline{0} & \cdots \\ \underline{0} & \underline{0} & \underline{0} & \omega.^4 & \underline{0} & \underline{0} & \cdots \end{bmatrix}}_{n} \tag{2}$$

$$\mathbf{\Omega_b} = \begin{bmatrix} \mathbf{P}^T & \mathbf{Q}^T \\ \mathbf{Q}^T & -\mathbf{P}^T \end{bmatrix} \begin{bmatrix} \mathbf{I}_\varepsilon & \mathbf{0}_\varepsilon & -\mathbf{I}_\varepsilon & \mathbf{0}_\varepsilon \\ \mathbf{0}_\varepsilon & -\mathbf{I}_\varepsilon & \mathbf{0}_\varepsilon & \mathbf{I}_\varepsilon \end{bmatrix} \cdot \\ \cdot \underbrace{\begin{bmatrix} \omega.^0 & \underline{0} & \underline{0} & \underline{0} & \omega.^4 & \underline{0} & \cdots \\ \underline{0} & \omega.^1 & \underline{0} & \underline{0} & \underline{0} & \omega.^5 & \cdots \\ \underline{0} & \underline{0} & \omega.^2 & \underline{0} & \underline{0} & \underline{0} & \cdots \\ \underline{0} & \underline{0} & \underline{0} & \omega.^3 & \underline{0} & \underline{0} & \cdots \end{bmatrix}}_{m+1} \tag{3}$$

From the above, the parameter vector $\mathbf{\Theta}$ can be found by using the inversion $\mathbf{\Theta} = \mathbf{\Omega}^{-1}\mathbf{Y}$ if there is an even number of unknown parameters, and the pseudo-inversion $\mathbf{\Theta} = \left\{\mathbf{\Omega^T\Omega}\right\}^{-1}\mathbf{\Omega^T Y}$ if the number of unknown parameters is odd. Alternatively, in the case of the odd number of parameters, the last row in (3) can be omitted and true inversion used. A thorough discussion, and a *modification necessary for astatic SISO systems* which represent realistic marine vehicle models is given in Miskovic *et al.* (2009a,b).

More advanced results, taking into account the physical principles at work behind the construction of non-linear vessel dynamic models and real-world experimental data on the use of this methodology to identify vessel dynamics and consequently, auto-tune I-PD surge speed and heading rate controllers can be found in Miskovic *et. al* (2009c).

5.2 Distributed Coordinated And Cooperative Control

A framework for distributed coordinated guidance of unmanned vessels has been developed in LABUST, based on the methodology of virtual potentials or decentralized control functions.

Let each obstacle and way-point in the 2D mission-space of the AUV be uniquely described by a *potential distribution function*. Let this function $P_i(\boldsymbol{x}(k)) : \mathbb{R}^2 \setminus \mathbb{A}_i \rightarrow \mathbb{R}_0^+$ map all points in the mission-space to the exclusion of the interior of the obstacle $\mathbb{A}_i$ [9] centered [10] at $\boldsymbol{x}_i$, the *location of the obstacle*. Let every $P_i \equiv p_i \circ d_i$, i.e. let P_i be uniquely decomposable into a potential function that varies with Euclidean distance, p_i, and the distance between an obstacle or a way-point and the location of the AUV $\boldsymbol{x}(k) \in \mathbb{R}^2$ itself, d_i. Let every p_i belong to the class $\mathcal{P} = \{p_{obs}(d), p_{wp}(d)\}$, with p_{obs}, given in (4) being the form of potential distribution function used for obstacles and p_{wp}, given in (5) being the form of potential distribution function used for way-points.

$$p_{obs}(d) = \exp\left(\frac{A^+}{d}\right) - 1 \tag{4}$$

$$p_{wp}(d) = \begin{cases} d \le r: & \frac{A^-}{2r}d^2 + \frac{A^-}{2}r - A^- d_0 \\ d > r: & A^-(d - d_0) \end{cases} \tag{5}$$

Then, the *irrotational accleration along an ideal conservative trajectory*, $\boldsymbol{a} = \operatorname{grad} P$, having in mind that potentials are additive, i.e. $P = \sum_i^N p_i \circ d_i(\boldsymbol{x}(k))$, can be written as:

$$\boldsymbol{a} = \sum_i^N \operatorname{grad} p_i(d_i(\boldsymbol{x}(k))) = \sum_i^N a_i \hat{\boldsymbol{a}}_i \tag{6}$$

Where $\hat{\boldsymbol{a}}_i$ is the unit-vector denoting the direction of the gradient of p_i, being $(\boldsymbol{x}_i - \boldsymbol{x}(t))/\|\boldsymbol{x}_i - \boldsymbol{x}(t)\|$ for waypoints, and dependent upon the geometry of $\mathbb{A}_i$ for obstacles.

With the addition of a *rotor* or *curl* as described in Barisic *et al.* (2008):

$$\boldsymbol{a}_i^{rot} = a_i \cdot \hat{\boldsymbol{a}}_i^{rot} \tag{7}$$

$$\hat{\boldsymbol{a}}_i^{rot} = \begin{cases} p_i \sim p_{obs}, \sin(\rho) \le 0: & \begin{bmatrix}\hat{\boldsymbol{a}}_i^{\mathrm{T}} \mid 0\end{bmatrix}^{\mathrm{T}} \times \begin{bmatrix} 0 & 0 & 1\end{bmatrix}^{\mathrm{T}} \\ p_i \sim p_{obs}, \sin(\rho) > 0: & \begin{bmatrix} 0 & 0 & 1\end{bmatrix}^{\mathrm{T}} \times \begin{bmatrix}\hat{\boldsymbol{a}}_i^{\mathrm{T}} \mid 0\end{bmatrix}^{\mathrm{T}} \\ p_i \sim p_{wp}: & \mathbf{0} \end{cases} \tag{8}$$

Where ρ is $\angle(\overline{WP_c\,AUV}, \overline{WP_c\,W_i})$, the azimuth of the AUV w.r.t. the line through the waypoint WP_c and W_i, and $c_i = \arg\min_j \|\boldsymbol{x}_i - \boldsymbol{x}_j\|, \forall j\ p_j \sim p_{wp}$, is the index of the waypoint closest to the i-th obstacle.

With that, the *acceleration along an ideal conservative trajectory* becomes:

$$\boldsymbol{a}_\Sigma = \sum_{i=1}^N a_i \cdot \hat{\boldsymbol{a}}_i + a_i \cdot \hat{\boldsymbol{a}}_i^{rot} = \sum_{i=1}^N a_i(\hat{\boldsymbol{a}}_i + \hat{\boldsymbol{a}}_i^{rot}) \tag{9}$$

A stable third-order decoupled linear dynamics of the closed-loop of surge and yaw rate control of the AUV (Miskovic *et al.* (2009a,b)) are assumed, $\deg G_V(z) = \deg G_\omega(z) = 3$. These dynamic yield a non-ideal or *real dissipative trajectory* followed by the AUV based on the formation of command-signals $v_c(k)$ and $\omega_c(k)$ as follows:

$$\boldsymbol{v}_c(k) = \frac{T}{2}\left(\boldsymbol{a}_\Sigma(k) + \boldsymbol{a}(k-1)\right) + \boldsymbol{v}(k-1) \tag{10}$$

$$\boldsymbol{v}_c(k) \equiv v_c \angle \varphi_c(k):$$

$$\varphi_c(k) = \operatorname{atan}_2 \frac{(\boldsymbol{a}_\Sigma(k) + \boldsymbol{a}(k-1) + \frac{2}{T}\boldsymbol{v}(k-1))\hat{\boldsymbol{\jmath}}}{(\boldsymbol{a}_\Sigma(k) + \boldsymbol{a}(k-1) + \frac{2}{T}\boldsymbol{v}(k-1))\hat{\boldsymbol{\imath}}} \tag{11}$$

$$\omega_c(k) = \frac{2}{T}\left(\varphi_c(k) - \varphi(k-1)\right) - \omega(k-1) \tag{12}$$

Where φ, ω, $\boldsymbol{a}$ and $\boldsymbol{v}$ are respectively the measured heading, yaw rate, acceleration and velocity of the AUV, and the quantities subscribed by c are the controller commands or variables otherwise used in the process of calculating the commands.

An in-depth discussion of the theory, as well as simulation and experimental results can be found in Barisic *et al.* (2008, 2009a,c).

[9] A connected, convex open subset of $\mathbb{R}^2$.

[10] Contained in an open ε-ball centered at $\boldsymbol{x}_i$.

6. CONCLUSIONS AND FURTHER WORK

The CURE project has contributed immensely to the ability of LABUST to disseminate its applied research results. As a result, research activity has soared. LABUST has employed additional researchers with competence grounded in previous professional experience. The programme of international interdisciplinary field training has allowed LABUST to grow aware of actual problems encountered by potential end-users (and thus – market drivers to possible future spin-off ventures). The programme has also allowed LABUST to stand out as a capable research power-house with competence in organizing, fielding, and logistically supporting an interdisciplinary team of researchers and professionals in complex combined operations.

6.1 Future Work

(1) A new season of field-work and experimentation is due from March 2010 through October 2010 utilizing and integrating equipment mentioned in Section 3. Collaboration with domestic and regional scientists is invited.
(2) The organization of the 2. International Interdisciplinary Field Training Of Marine Robotics And Applications "Breaking the Surface 2010" is underway. More can be found out at *http://bts.fer.hr*.
(3) Collaboration on experiments with the ROV LATIS (Molnar, L. *et. al* (2005)) of the University of Limerick are expected in March and / or September 2010.
(4) Publication of newest research results is expected at MED'10 [11], CAMS'10 [12], and AUV'10 [13].
(5) A new cycle of research secondments is due for LABUST's researchers in latter half of 2010 and in 2011.
(6) A stipend for a visiting expert for up to three months in 2010 is available.

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