Annual Reviews in Control 32 (2008) 263–269

Annual Reviews in Control

www.elsevier.com/locate/arcontrol

Trends in marine control systems

G.N. Roberts

Control Theory and Applications Centre, Faculty of Engineering and Computing, Coventry University, United Kingdom

Received 11 November 2007; accepted 31 August 2008

Abstract

Sperry and Minorski are names synonymous with the development of the first steering autopilots and it is well known that their pioneering work and seminal publications led to the introduction of the three-term or proportional-integral-derivative (PID) controller for automatic ship steering. Despite the efforts and enthusiasm of numerous researchers, from all areas of control engineering, to persuade industry to adopt more sophisticated controller designs, PID controllers remain the industry preference and industry standard for automatic control systems. The paper sets the scene with a review of the early developments of automatic control systems for ship steering, which led to Sperry's *automatic pilot*. This is followed by an overview of developments in roll stabilization; integrated ship steering and roll stabilization; unmanned underwater vehicles and unmanned surface vessels. Consideration of over 750 papers presented at the 13 conferences and workshops sponsored by the IFAC Technical Committee on Marine Systems in the period 1992–2008 is used to track recent trends in marine control systems and are the basis for some thoughts on possible future directions for the marine control community.

Keywords: Ship steering; Ship roll stabilization; Unmanned marine vehicles

1. Introduction

It was not until the industrial revolution that methods for automatically steering ships were first contemplated, although the first ship autopilots did not come into use until the first part of the 20th century. Nevertheless, before the development of autopilots could progress it was necessary to devise a powered rudder or steering engine. The motivation for a steering engine came primarily from the naval requirement for warships to undertake high-speed manoeuvres. Bennett (1979) reports that in the late 1860s the British Admiralty equipped several of their sailing ships with various types of steering engines, many of which were based on a steam-hydraulic system.

Once powered rudders or steering machines became commonplace, attention turned to providing inputs to these devices from suitable heading seeking equipment. Fossen (2000) describes how the development of the electrically driven gyrocompass was pivotal in the evolution of ship autopilots. Electrically driven gyrocompasses overcame the problems associated with magnet compasses which had their readings corrupted by local magnetic fields and the electrical systems in ships, torpedoes and submarines. The first electrically driven gyroscope was demonstrated in 1890, in 1908 Anschutz patented the first North seeking gyrocompass and in 1911 Sperry patented his ballistic compass, which included vertical damping. The invention of the electrically driven gyrocompass is arguably the most important breakthrough in ship control systems design.

The paper is organised as follows. Section 2 considers the origins of automatic steering of ships which resulted in the development of the all important PID controller; ship roll stabilization is covered in Section 3, where, after a brief history of active fin roll stabilization, the concept of rudder roll stabilization and integrated fin/roll stabilization is discussed. Section 4 briefly looks at developments in unmanned underwater vehicles and unmanned surface vehicles. The contributions which IFAC conferences and workshops have made to advances in marine control systems is outlined in Section 5. Concluding remarks are given in the final section.

The paper does not cover aspects of control of ancillary shipborne equipment.

2. Automatic ship steering

The process of automatically steering ships has its origins going back to the time when early fishermen would bind the

E-mail address: geoff.roberts@coventry.ac.uk.

1367-5788/$ – see front matter
doi:10.1016/j.arcontrol.2008.08.002

tiller or rudder of their boats in a fixed position to produce an optimal course in order to release extra manpower to assist with the launching and recovery of nets. Most likely the criteria for selecting the optimum course would be to minimise induced motions and to maintain a course which would help with the deployment or recovery of the nets. However, it was not until the first quarter of the 20th century that a number of automatic steering systems for ships were devised. The idea of ‘‘check helm’’ or derivative action was introduced by Sir James Henderson who was granted a patent in 1913 for his ‘‘automatic steering device’’ which used both heading error and heading error rate in the feedback loop. However, the major contributions to the development of practical ship steering systems were made by the Sperry Gyroscope Company. Allensworth (1999) describes how Elmer Sperry constructed the first automatic ship steering mechanism in 1911 which he called the *automatic pilot* or *gyropilot.* Sperry’s gyropilot (Sperry, 1922) was known as *Metal Mick* because in its operation it appeared to replicate the actions of an experienced helmsman. Sperry had observed that a helmsman ‘‘eases’’ the rudder as the ship responds and tended to apply rudder proportional to heading error. He also observed that an experienced helmsman would reduce the rudder angle as the heading error reduced and would apply counter rudder to negate the possibility of overshoot. To account for these human actions he included an ‘‘anticipator’’ that automatically adjusted the backlash of the controller according to the heading angle, in effect resulting in a simple adaptive autopilot.

The work of Minorski (1922) is also regarded as making key contributions to the development of automatic ship steering systems. Minorski’s main contribution was the theoretical analysis of automatic steering and the specification of the three-term or proportional-integral-derivative (PID) controller for automatic ship steering. As in the case of Sperry’s work, his PID controller designs were predicated on visual observation of the way the experienced helmsman would steer a ship. He acknowledged that helmsmen would anticipate ship motions before applying rudder corrections but more importantly he postulated that they possessed the ability to judge angular velocity, i.e. yaw rate, thereby effecting derivative control. Indeed it is worth noting that the ability of a human operator to estimate innately velocity is now widely accepted in human factors research.

The important legacy of Sperry and Minorski’s innovative work and seminal publications is the three-term or proportional-integral-derivative (PID) controller. Whilst Minorski and Sperry developed the PID controller for automatic ship steering, PID controllers largely remain the industry-preference and industry-standard for automatic control systems. This is despite the efforts and enthusiasm of numerous researchers, from all areas of control engineering, to persuade industry to adopt more sophisticated controller designs.

3. Active roll stabilization

Active roll stabilization of ships is achieved either by the controlled movement of water within the ship structure, i.e. active controlled tanks, or the controlled movement of actuators extending from the ship’s hull, i.e. fin roll stabilization (FRS), rudder roll stabilization (RRS) or integrated fin rudder roll stabilization (INFRRS). Ship roll stabilization using hydraulically operated stabilising fins and/or the rudder are areas where researchers have dissipated considerable efforts, over many years, to design active control systems capable of ameliorating ship roll motions. The introduction of roll stabilization of ships came about to meet the separate needs of merchant fleets and the naval community. In the former the driving reason was passenger comfort and cargo stability. Although active roll stabilization systems use valuable passenger and/or cargo space, and in the case of FRS introduce more drag, it should be noted that reductions in energy costs are achieved by virtue of ‘stabilized ships’ being able to remain on course during inclement sea conditions, rather than having to divert to headings where the adverse effects of roll motions are less likely. The impetus for roll stabilization in naval operations was to meet the operational requirement of maintaining stable weapon platforms, which was given further impetus by the introduction of ship-borne helicopters in the 1950s. In addition, the adverse effects which *Motion Induced Interruptions* and *Motion Sickness Incidence*, resulting from prolonged exposure to excessive ship motions (Perez, 2005; Sharif, Roberts, French, & Sutton, 1993; Tang & Wilson, 1992), have on the safety and efficiency of personnel further reinforces the efficacy of active roll stabilization.

In the following sections an overview of the development of FRS and RRS will be presented; it will be shown how the integration of FRS and RRS into INFRRS enables roll stabilization capability to be maximized. The section concludes with a brief introduction to recent developments in actuator technology and switched control for roll stabilization.

3.1. Fin roll stabilization (FRS)

Much of the early research on FRS was undertaken in the UK, funded by *The Admiralty*, who recognising the operational advantages of such systems became the prime user and it is significant that every combatant warship of frigate size and above built for the Royal Navy since 1956 has been fitted with FRS. Details of early installations of FRS are given in (Allen, 1945). The control strategy employed with early FRS installations comprised a crude mechanism utilising a velocity-sensing gyro whereby the fins were tilted to their maximum deflection to oppose roll motion whenever the roll velocity exceeds a preset level. Whilst this on–off control strategy achieved reductions in major roll excursions it was judged as being unsatisfactory because of the impulses resulting from rapid stabilising fin movement and the resulting short periods of roll motion. The drawbacks of the on–off control led to the development of the first continuous FRS controller, as described by Bell (1957a, 1957b). With the continuous controller, roll angle in addition to roll velocity was used to drive the cam, the following lever of which was used to control the hydraulic power to the stabilising fins and therefore their displacement. Bell’s mechanical P + D controller was later enhanced by the addition of an accelerator term to improve its anticipation qualities (rather like Sperry's gyropilot, described in Section 2), thereby producing the standard PID controller for FRS (Connolly, 1968). PID control was used for FRS for many years, albeit the mechanical linkages were replaced by electronic controllers and more recently their digital equivalents. Whilst controller designs were relatively static over a long period some work on stabilising fins designs was undertaken in order to maximise roll reduction, For example Lloyd (1974), and it was not until research into RRS and INFRRS that alternative controller designs were examined.

3.2. Rudder roll stabilization (RRS)

RRS uses the inward heel caused by initial rudder deflection to produce the righting moment to reduce roll motion induced by waves. The success of RRS is dependent on the dominant time constants of the roll control loop being at least a factor of 10 faster that those of the yaw loop, i.e. the roll and yaw control loops are decoupled, thus permitting 'fast' rudder movements to counteract roll motion, whilst the low frequency rudder deflections control steering. It has been shown that rudder speeds in excess of $12^\circ\ s^{-1}$ (typically $18^\circ\ s^{-1}$) are necessary if RRS is to be as effective as FRS (Roberts, 1993; van der Molen, 2004), which means that RSS is not really suitable for retrofitting, unless costly upgrading of the steering gear is included in the retrofit budget. The possibility of RRS was first reported by (Taggart, 1970) during manoeuvring trials on board SS American Resolute, undertaken to investigate complaints by the crew of excessive roll motions induced by the rudder. Taggart found that at high ship speeds in following seas it was possible to achieve synchronism between wave encounter and ship roll frequency, and when under autopilot control the rudder exacerbated the roll when attempting to correct yaw excursions. Taggart reasoned that the forces which generated such large roll motions could be harnessed to reduce roll motion induced by sea disturbances. One of the first RRS designs was proposed in 1972 (Cowley & Lambert, 1972); since that time RRS has been the focus of much research activity with contributions from researchers in several countries. Major contributions to RRS came from research groups in The Netherlands and Denmark (Amerongen, Klugt, & Naute Lemke, 1990; Blanke, Adrian, Larsen, & Bentsen, 2000; Klugt, 1987), with both groups examining alternative control strategies such as Model Reference Adaptive Control and H-Infinity, and taking designs from inception to full scale sea trials and commercial realisation.

3.3. Integrated fin rudder roll stabilization (INFRRS)

With INFRRS the two control surfaces (rudder and stabilising fins) are used in concert to simultaneously control roll and yaw motions. As stated previously ship roll and yaw dynamics need to be decoupled so that the yaw control (autopilot) is not affected by the RRS loop, and as is the case with RRS, INFRRS requires fast rudder speeds for an effective RRS loop. However, it is possible to achieve some roll reduction with standard rudder speeds such that INFRRS offers improved roll stabilization over simple FRS, and also allows three distinct modes of roll stabilization, i.e. FRS alone, RRS alone or INFRRS. One of the early proposals for INFRRS is given in (Kallstrom, 1981). Roberts, Sharif, Sutton, & Agarwal (1997) report on the first full scale trials using LQG and H-Infinity designs for the INFRRS controllers for a warship having a maximum rudder speed of $6^\circ\ s^{-1}$. This work was also one of the first reported implementation of H-Infinity controllers. More recent contributors to INFRRS include (Tanguy et al., 2003) who examines multi-objective optimisation of PID and H-Infinity controllers, Katebi (2004) and Perez (2005) report work focussed on Model Predictive Control.

3.4. Switched control for INFRRS

One of the difficulties encountered in designing a suitable controller for ship roll stabilization is the production of a controller that will be effective for all ship speeds, sea states and wave encounter angles. In most applications controller performance is tuned or optimised to minimise roll motions at the ship's natural rolling frequency, in beam seas. Such a design strategy for FRS led to minimal roll reduction in quartering and following seas. Early PID-based RRS designs often exhibited roll magnification in quartering seas, which could only be overcome by de-tuning the PID designs or utilising other sub-optimal/robust controller designs whereby roll reduction could be achieved for all encounter angles, at a cost of reduced roll reduction in beam seas. This design trade-off led to the proposal to design a bank of controllers for a range of ship speeds, sea states and encounter angles and to automatically switch to the appropriate controller. Switch control systems, or parallel multi-model control systems, have been an area of interest for some time (Narendra & Balakrishan, 1997). Some work has been reported using switched control for Unmanned Underwater Vehicles (Ippolitti, Jetto, & Longhi, 2006). The potential for enhancing roll stabilization performance using switched control was demonstrated by Crossland (2000), who produced enhanced roll stabilization using manual switching between a set of controllers. More recently work on Parallel Multi-Model Switched Control (PMMSC) for INFRRS (Roberts, Cournou, & Vinsonneau, 2006) has extended this concept further. Here the PMMSC algorithm uses a two-level hierarchical control strategy, where at the lower level a bank of controller pairs (fin roll and rudder roll controllers) each being tuned for a particular ship operating condition, i.e. speed, encounter angle and sea state, and at the upper level a decision maker decides which controller pair is most suited to the prevailing conditions and ensures that the appropriate controller pair is switched into operation. For this work the bank of PID controller pairs were designed for ship speeds of 8, 13 and 18 knots, at sea states 3 and 5, and for encounter angles of 0°, 30°, 60°, 90°, 120° and 150°. The decision to switch to an alternative controller pair was facilitated by interrogation of power spectral density histograms, computed from roll angle data. However, any change in ship's course or speed will be known *a priori*, a first guess (FG) controller can be switched into operation immediately steady conditions are achieved, and following the evaluation of the PSD histogram, the FG controller can be confirmed as correct, or otherwise. Detailed results from this study can be found in Roberts, Cournou, Vinsonneau & Burnham, 2006.

3.5. Actuator technology developments

As stated in Section 3.2, one of the requirements for RRS is that rudder speeds in excess of $12^\circ\ s^{-1}$ are necessary if RRS is to be as effective as FRS. Whilst the implementation of an INFRRS controller requires relatively few additions, increasing rudder speeds from $6^\circ\ s^{-1}$ to 12 or $18^\circ\ s^{-1}$ necessitates costly replacement and/or updating of the steering machine. The requirement for a high-speed rudder has delayed the take up of RRS and INFRRS by ship operators. However, recent work on the development of Electrical Actuation of Hydrodynamic Control Surfaces (ELAHCS). Stafford & Osborne (2008) have shown that the use of ELAHCS for stabilisers or rudders has significant advantages over their current hydraulically operated counterparts. For example, it is suggested that use of ELAHCS will result in: improved reliability; low planned maintenance requirements; no high pressure seals and consequently no leaks; no pumps and drive couplings; no hoses, fittings, filters, reservoirs, accumulators or valves; reduced energy usage; reductions in setting-to-work times; reductions in consumables (i.e. no oil and cleaning/flushing fluid); reduced weight and space, resulting is reduced life costs. Importantly, using ELAHCS technology for rudder systems will enable faster rudder speeds to be easily achieved, which in turn will facilitate the implementation of RRS and INFRRS.

4. Unmanned marine vehicles

Although Bourne can be credited with producing the first conceptual design for a submarine in 1578, the first one to be built was constructed in 1620 by van Drebbel. Nevertheless, it was not until 1776 that a submarine was specifically launched to take part in naval operations. Bushnell's submarine, the *Turtle*, was designed to destroy the Royal Navy men-of-war which were participating in naval blockages during the American War of Independence. Fortunately for the British fleet, the attacks by the human powered *Turtle* were unsuccessful. The *Turtle's* single crew member blamed the ineffectiveness of the assaults on the inability to lay 150 pound charges against the hulls of the ships owing to their reputed copper sheathing. In actual fact, the British warships were not sheathed. A more probable explanation has been postulated by Coverdale & Cassidy (1987), who suggest that it was due to the crew member being physically exhausted and affected by the build up of unacceptable carbon dioxide levels in the vessel by the time it reached an intended target. Reader, Walker, & Hawley (1989) light-heartedly suggest that this may have been the initial impetus for the search for unmanned underwater vehicles (UUVs) Clearly, since those pioneering days, manned submarine technology has advanced dramatically. However, the common potential weaknesses throughout their evolution have been the cost and reliance on humans to perform operational tasks.

The ancestry of the modern UUV may be traced back to the self-propelled torpedo perfected in 1868 by Whithead. Some of the earliest more significant developments in UUV technology can be attributed to the cable controlled underwater recovery vehicle design and construction programme instigated by the US Navy in 1958. Indeed, in 1963, such a craft was used in the search for the ill-fated USS *Thresher*, which tragically sank off the New England coast in 1400 fathoms of water. Later, in 1966, another was used to help recover the US Navy hydrogen bomb lost off the coast of Palomares, Spain. Notwithstanding those successes and the accompanying publicity, the commercial potential of UUVs was not recognized until the discovery of the offshore oil and gas supplies in the North Sea. Specifically, remotely operated vehicles (ROVs) began and continue to be used extensively throughout the offshore industry, whereas in both the naval and commercial sectors, autonomous underwater vehicle (AUV) usage was limited. Nonetheless, interest in the possible use of both types has heightened, prompted by the needs of the offshore industry to operate and explore at extreme depths in a hostile environment, and the operational requirements of navies to have low cost assets capable of undertaking covert surveillance missions, and performing mine laying and disposal tasks.

It should be noted that the phrase ‘‘unmanned underwater vehicle’’ as used here is a generic expression to describe both an AUV and ROV. An AUV being a marine craft which fulfils a mission without being constantly monitored and supervised by a human operator, whilst a ROV is a marine vessel that requires instructions from an operator via a tethered cable or acoustic link. Also in some more recent literature the term ‘‘unmanned’’ is being replaced by ‘‘uninhabited’’.

Recent developments in the design and development of unmanned surface vehicles (USVs) and unmanned semi-submersible craft (USSC) have brought new classes of unmanned marine vehicles (UMVs). From a historical perspective as highlighted by Corfield & Young (2006) the use of an USV provided a solution to the problem of a naval blockade in 1718. They also mention briefly the fire ships employed by Howard and Drake. In one particular instance during the summer of 1588, Howard and Drake arranged for eight fire ships (USVs) to be sent against the Armada which caused the majority of the Spanish ships to break formation and leave their safe anchorage in Calais for the open sea. Soon after this incident the Battle of Gravelines ensued.

As stated in Section 2 the process of automatically steering ships has its origins going back to the time when early fishermen would bind the tiller or rudder of their boats in a fixed position to produce an optimal course. However, by way of a contradiction, Slocum (1900) recounts an incident where a highly experienced shipmaster of that era served as an expert witness in a famous murder trial in Boston, USA, in which he stated that a particular sail ship could not hold her course long enough for the steersman to leave the helm to cut the throat of its captain! For some it will also be of interest to know that Slocum was the first solo global circumnavigator and to honour this achievement a class of unmanned underwater glider has been named after him.

5. IFAC's contributions to marine control systems

The previous sections present an overview of developments in ship control and UMVs. In this section an examination of the contribution which IFAC has made to these areas is presented. This is based on an analysis of over 750 papers presented at the 13 conferences and workshops sponsored by the IFAC Technical Committee (TC) on Marine Systems in the period 1992–2008. Papers sponsored by the TC for presentation at the triennial IFAC World congresses are not included in this analysis. The two main events sponsored by the TC are the Control Applications in Marine Systems (CAMSs) and the Manoeuvring and Control of Marine Craft (MCMC), conference series, each of which are held on 3-year cycles. MCMC2006 and CAMS2007 were both the 7th conference in the series. In 2003 the TC sponsored the first workshop on guidance and control underwater vehicles (GCUV'03), the second event in this series, renamed Navigation guidance and control of underwater vehicles (NGCUV'08) was held in Limerick, Ireland 8–10 April 2008.

Table 1 shows a breakdown of papers presented at the 13 TC sponsored conferences and workshops in the period 1992–2008. These very broad classifications are used specifically to group papers into generic areas and also separate those papers associated with ships and with UMVs. The column listing 'other papers' is used to locate papers which do not concern steering, roll stabilization and UMVs.

The broad-brush approach used to populate Table 1 enables an initial evaluation of trends in marine control, the first of which is the growth in the number of papers concerning UUVs. For example, from MCMC'2000 the number of papers concerning UUVs has not been less than 26% of the total, i.e. 26% for CAMS'01 and CAMS'04, 32% for MCMC'2000, MCMC'03 and CAMS'07 and the top 43% for MCMC'06. It was this increase in papers concerning UUVs, which led directly to the organisation of GCUV'03. Papers concerning UUVs presented at the IFAC sponsored events listed in Table 1 provide excellent background material of the developing interest and activity in this area. Three noteworthy publications in this area, which contain a range of high-quality papers are Griffiths (2002), Roberts & Sutton (2006), and Sutton & Roberts (2007).

A second trend which can be identified from Table 1 is the more recent appearance of papers concerning USVs. Five papers for CAMS'07, an increase from just two papers at MCMC'06 may well mean that there will be more papers in this area for future MCMC and CAMS meetings. A possible side effect of the increase in UMV activity will be the need to establish, on an international level, the legal status of unmanned marine vehicles. This is because it is current practice to consider unmanned vessels to be abandoned, and consequently having potential for salvage operators.

Table 1 also indicates that activity in other 'traditional areas' such as ship steering, roll stabilization, modelling/identification, dynamic positioning and fault detection/accommodation remain fairly constant. However, the broad-brush approach used to populate Table 1, whilst useful to form clusters, and hence identify trends, does not provide any information on the various focuses within the clusters. For example the ship steering category includes autopilots and harbour operations such as automatic berthing. Further examples are presented in the following sections.

5.1. Roll stabilization

During the period of this study a total of 44 papers were presented on roll stabilization. Further scrutiny of these 44 papers reveals that just one paper concerned stabilization by active tanks, nine papers addressed traditional fin/roll stabilization with the remaining papers split almost equally on rudder roll stabilization and integrated fin/rudder roll

Table 1
Breakdown of papers presented at TC sponsored conferences and workshops 1992–2008.

Event/location	No of papers	Roll stabilization	Ship steering	Modelling/ identification Ships/UUVs	Dynamic positioning/ tracking control	Fault detection/ reconfiguration	Hydro-dynamics	Other control[a]	UUVs	ASVs
NGCUV'08 Ireland	39								39	
CAMS'07 Croatia	76	3	9	3/2	9	4		17	24	5
MCMC'06 Portugal	102	4	23	5/3	11	4		8	42	2
CAMS'04 Italy	81	8	14	3	7	3	1	24	21	
MCMC'03 Spain	60	3	6		7	3	2	19	19	1
GCUV'02 UK	40								40	
CAMS'01 UK	78	1	19	6	4	7		21	20	
MCMC'00 Denmark	69	7	8	4	9	2		17	22	
CAMS'98 Japan	53	3	13	5	12	4		10	6	
MCMC'97 Croatia	33		7		6	3	5	1	8	
CAMS'95 Norway	61	9	16		10	2		12	12	
MCMC[b]'94 UK	32	2	12	2			8	7	1	
CAMS'92[c] Italy	39	4	12		2	1		14	6	

[a] Papers concerning on-board ancillary machinery.
[b] This was the 3rd MCMC meeting but the first to be co-sponsored by IFAC.
[c] Actually an IFAC Workshop on Artificial Intelligence Control and Advanced Technology in Marine Automation.

stabilization. Clearly, both rudder roll and integrated fin/roll stabilization remains to be a relative hot topic.

5.2. UUVs

The scope and range of material covered in the 221 papers (31%) concerning UUVs may be decomposed into the following 10 main sub-groups, i.e.

- automatic control
- system identification
- navigation
- mission planning
- obstacle avoidance
- underwater vision
- control architectures
- fault detection and accommodation
- intervention vehicles
- cooperative behaviours

Although many of the sub-groups are interconnected, approximately 30% of the papers address control applications; 18% concern navigation, mission planning and obstacle avoidance; 10% are focussed on machine vision; 8% on control architectures and 7% on cooperative behaviour. Interestingly contributions to cooperative behaviours have increased in the last 3 years. Surprisingly, papers concerning fault detection and accommodation and intervention applications have been relatively low. The most significant difference between the papers concerning UUVs and those addressing ship control issue is that most of the UUV work is undertaken using actual vehicles, rather than simulation studies, which, for obvious reasons, is commonplace for ship control studies.

5.3. Intelligent systems

The use of intelligent paradigm such as fuzzy logic (FL), Artificial Neural Networks (ANNs) and combinations thereof have received considerable attention by the marine community. Fuzzy, fuzzyneural and neurofuzzy autopilots have been proposed, discussed and evaluated, for example. (Amerongen, Nauta Lemka, & Veen, 1977; Omerdic, Roberts, & Vukic, 2003; Sutton & Jess, 1991). It is believed that the first commercial fuzzy autopilot was developed by Polkinghorne, Roberts, Burns, & Winwood (1995). Although intelligent approaches continue to be reported for ship and UMV applications, it appears that their early promise has not resulted in prolific applications, probably because of difficulties in guaranteeing performance and stability.

6. Concluding remarks

The paper has discussed key developments in ship control and unmanned marine vehicle operations, and the contribution which IFAC has made, and will continue to make, to the dissemination of new ideas and experiences in marines control systems. It is accepted that the work presented is limited to considering only IFAC sponsored events and that there are other national and international organisations making similar contributions. Over 700 papers presented at 13 international meetings does however, engender some confidence in trends in marine control identified herein.

Since the early pioneering work on unmanned underwater vehicles, which have been briefly mentioned, worldwide interest is gathering a pace into the design and development of all classes of UMVs as they are now considered by many as being able to provide cost-effective solutions to a number of commercial, naval, scientific and security applications, which now includes the integration of multiple autonomous air, surface and underwater vehicles.

Clearly, there will be technical challenges to surmount, which will provide the motivation for research proposals, research programmes and opportunities to secure funding.

References

Allen, J. E. (1945). The stabilisation of ships by activated fins. *Transactions Institute of Naval Architects, 87*, 123–159.

Allensworth, T. (1999). A short history of Sperry Marine. http://www.sperry-marine.northropgrumman.com/Company-Information/Corporate-History/Sperry-History/.

Amerongen, J., Nauta Lemka, H. v an, Veen, R., & van der, J. C. T. (1977). An autopilot for ships designed with fuzzy sets. *IFAC conference on digital applications for process control* (pp. 479–487).

Amerongen, J. v an, Klugt, P. G. M., & Naute Lemke, H. van.. (1990). Rudder roll stabilisation of ships. *Automatica, 26*, 670–690.

Bennett, S. (1979). A history of control Engineering 1800–1930. IEE Control Engineering Series. ISBN 0863410472.

Bell, J. (1957a). Ship steering controls and computation. *Transactions Institute of Naval Architects,* 724–729.

Bell, J. (1957b). Ship stabilisation: automatic controls, computed in practice. *Transactions IEE Part B, 104*, 20–26.

Blanke, M., Adrian, J., Larsen, K. E., & Bentsen, J. (2000). Rudder roll damping in coastal region sea conditions. In *Proceedings of the 5th IFAC Conference on Manoeuvring and Control of Marine Craft (MCMC2000)* (pp. 39–44).

Connolly, J. E. (1968). Rolling and its stabilisation by active fins. *Transactions Royal Institute of Naval Architects, 111*, 21–48.

Corfield, S. J., & Young, J. M. (2006). Unmanned surface vehicles–game changing technology for naval operations. In G. N. Roberts & R. Sutton (Eds.), *Advances in unmanned marine vehicles* (pp. 311–326). IEE Control Engineering Series.

Coverdale, A., & Cassidy, S. (1987). The use of scrubbers in submarines. *Journal of Naval Engineering, 30*(2), 528–544.

Crossland, P. (2000). The effect of roll stabilisation controllers on warship operational performance. In *Proceedings of the 5th IFAC Conference on Manoeuvring and Control of Marine Craft (MCMC2000)* (pp. 31–37).

Cowley, J. B. & Lambert, T. H. (1972). The use of the rudder as roll stabiliser. *Proceedings of the 3rd Ship Control Systems Symposium, Vol. 2*. Bath.

Fossen, T. I. (2000). A survey of nonlinear ship control: From theory to practice. *5th IFAC Conference Manoevring and Control of Marine Craft (MCM2000)* (pp. 1–16).

Griffiths, G. (Ed.). (2002). *Technology and Applications of Autonomous Underwater Vehicles (Ocean Science and Technology)*. CRC Press. ISBN 10: 0415301548.

Ippolitti, G., Jetto, L., & Longhi, S. (2006). Switching-based supervisory control of underwater vehicles. In G. N. Roberts & R. Sutton (Eds.), *Advances in unmanned marine vehicles* (pp. 105–121). IEE Control Engineering Series.

Kallstrom, C. G. (1981). Control of yaw and roll by rudder/fin stabilisation. *6th Ship Control System Symposium, Vol. 2*.

Katebi, M. R. (2004). A two layer controller for integrated fin and rudder roll stabilisation. *IFAC Conference on Control Applications in Marine Systems (CAMS04)* (pp. 101–106).

Klugt, P. G. M. van der. (1987). Rudder roll stabilization. PhD Thesis. Van Rietschoten and Houwens BV, Rotterdam.

Lloyd, A.R.J.M.. (1974). *Roll stabiliser fins: A design study.* Trans. Royal Institute of Naval Architects. pp. 233–254.

Minorski, N. (1922). Directional stability of automatically steered bodies. *Journal of American Society of Naval Engineers, 34*, 280–309.

Morse, A. S. (1996). Supervisory control of families of linear set-point controllers. Part 1. Exact matching. *IEEE Transactions on Automatic Control, 41*, 1413–1431.

Narendra, K. S., & Balakrishan, J. (1997). Adaptive control using multiple models. *IEEE Transactions on Automatic Control, 42*, 171–187.

Omerdic, E., Roberts, G. N., & Vukic, Z. (2003). A fuzzy track-keeping autopilot for ship steering. *IMarEST Proceedings: Journal of Marine Engineering and Technology, A2*(2), 23–35.

Perez, T. (2005). *Ship motion control: Course keeping and roll Stabilisation using rudder and fins*. London: Springer-Verlag. ISBN 1-85233-959-4.

Polkinghorne, M. N., Roberts, G. N., Burns, R. S., & Winwood, D. (1995). The implementation of fixed rulebase fuzzy logic to the control of small surface ships. *Control Engineering Practice, 3*(3), 321–328.

Reader, G. T., Walker, G., & Hawley, J. G. (1989). Non-nuclear power plants for AUVs. *5th International Symposium on Untethered Submersable Technology.* University of New Hampshire. pp. 88–99.

Roberts, G. N. (1993). A note on the applicability of rudder roll stabilisation for ships. *American Control Conference,* 2403–2407.

Roberts, G. N., Sharif, M. T., Sutton, R., & Agarwal, A. (1997). Robust control methodology applied to the design of a combined steering/stabiliser system for warships. *IEE Proceedings Control Theory and Applications, 144*(2), 128–136.

Roberts, G. N., & Sutton, R. (Eds.). (2006). *Advances in Unmanned Marine Vehicles*. IEE Control Engineering Series. ISBN 10 0863414508.

Roberts, G. N., Cournou, V., Vinsonneau, B., & Burnham, K. J. (2006). Parallel multi-model switched control for ship roll Stabilization. *Proceedings of the IMechE Proceedings Part M: Journal of Engineering for the Maritime Environment, 20*(M2), 53–65.

Sharif, M. T., Roberts, G. N., French, S. A., & Sutton, R. (1993). Lateral force stabilization: A comparison of controller designs. *10th Ship Control System Symposium, Vol. 5* (pp. 149–169).

Sutton, R., & Jess, I. M. (1991). A design study of a self-organising fuzzy autopilot for ship control. In *Proceedings of the IMechE, Vol. 205* (pp. 35–45).

Sutton, R., & Roberts, G. N. (Eds.). (2007). International Journal of Control, Special issue on Navigation Guidance and Control of Uninhabited Underwater Vehicles, Vol. 80, No. 7.

Slocum, J. (1900). *Sailing alone around the world*. Hazell Watson and Viney Ltd.

Sperry, E. A. (1922). Automatic steering. *Transactions, Society of Naval Architects and Marine Engineers,* 61–63.

Stafford, B., & Osborne, N. (2008). Technology development for steering and stabilizers, *Proc. IMechE Proceedings Part M: Journal of Engineering for the Maritime Environment, May* 2008, 222 (M2), pp 41-52.

Tang, A., & Wilson, P. A. (1992). Ship stabilization using lateral force estimator. *IFAC conference on Control Applications in Marine systems CAMS'92),* 139–141.

Taggart, R. (1970). Anomalous behaviour of merchant ship steering systems. *Marine Technology,* 205–207.

Tanguy, H., Lebret, G., & Doucy, O. (2003). Multi-objective optimisation of PID and H∞ fin/rudder roll controllers. In *Proceedings of the 5th IFAC Conference on Manoeuvring and Control of Marine Craft (MCMC'03)* (pp. 179–184).

van der Molen, G. (2004). Study on Effect of Rudder Slew Rate on Roll Stabilisation. Case Study Report ACT/CS27/2004. The Advanced Control Technology Club. Industrial Systems and Control Limited, Glasgow.

Professor Geoff Roberts is Professor of Mechatronic Systems in the Control Theory and Applications Centre, at Coventry University, UK. He has been active in the area of marine control systems for more than 20 years, making significant contributions to integrated ship steering and stabilization, intelligent autopilots and guidance and control of underwater vehicles. He is presently working on fault detection and data handling for underwater vehicles and parallel multi-model switched control for integrated ship roll stabilization. He is immediate past chairman of the IMechE Mechatronics Forum, a member of the IFAC Technical Committee on Marine Systems and a member of the IFAC Technical Committee on Mechatronic Systems.