Standing on the Shoulders of Giants: How the Maritime Industry can Leverage Developments in Autonomy from other Domains

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Synopsis

Autonomous maritime vessels have gained a considerable amount of attention in recent years due to their promise of reduced crew costs, increased safety and increased flexibility. This paper explores how the maritime industry can leverage the developments in autonomy and other systems to contribute to the continued drive towards autonomous maritime systems. First, several key technological areas associated with autonomous maritime systems are identified; including navigation and control systems, data transmission and electrical energy propulsion. These technical areas are then compared with other autonomous systems including autonomous aircraft, automobiles and spacecraft to find overlaps and similarities. A set of representative patents are determined for each technological area across each of the different autonomous systems and is then used to estimate a technological improvement rate for each technology-system pair. These technological improvement rates are implemented in a Monte-Carlo Markov Chain model to explore the effects of the timing of the adoption of autonomous systems in the maritime shipping industry. The model indicates a technological feasibility date of maritime autonomous systems beginning in 2028 when leveraging autonomous developments from other domains.

Keywords: Autonomous Maritime, Technology Forecasting, Logistics Modelling

1. History of Autonomous Maritime Vessels

Unmanned ships in their most basic form have existed for centuries as early fisherman tied their rudders in a fixed position to free up more manpower for fishing. Contributions toward unmanned ships continued in the 1860s, with the British Admiralty installing steering engines on their sailing ships; in 1911, with Elmer Sperry's gyropilot named 'Metal Mike', in 1922, with Minorsky's PID control and through the latter half of the 20th century with developments in dynamic positioning, way-point tracking and control, and non-linear ship control (Roberts et al, 2003; Fossen, 2000).

In recent years, the maritime world has been increasingly interested in exploring the benefits of autonomous and unmanned maritime vessels. For this paper, we will use the broad interpretation of autonomy as described by Schjølberg and Utne (2014) and Doris et al (1999) that describes direct line-of-sight remote control as the lowest level of autonomy and logic driven with only high level instructions given. This has resulted in a number of exploratory projects including the AAWA autonomous shipping concept (Rolls-Royce, 2016), the Yara Birkeland electric, autonomous ship (Skredderberget, 2018), a Japanese Trans-Pacific test (Cooper and Matsuda, 2017), the MUNIN research project (2016), an autonomous military ship (Mizokami, 2018), the DIMECC 'One Sea' Consortium (Haikkola, 2017), and a start-up company retrofitting old ships to be autonomous (Dillet, 2018).

Many of these efforts focus on the expected benefits of autonomous shipping, including reduced operational costs, reduced manning, reduced fuel consumption, improved lifestyles for the seafarers, and increased maritime shipping capacity (Kobyliński, 2018), among others. Others have shown more scepticism toward the proposed benefits and have pointed out many challenges that have not yet been solved including legal (Karlis, 2018), commercial (Willumsen, 2018) and operational (Kobyliński, 2018).

Karlis (2018) describes potential legal barriers to adopting new technologies arising from ambiguities in the International Convention for the Safety of Life at Sea (SOLAS), International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) and the 2016 Maritime Labour Convention (MLC) and provides suggestions to alleviate some of those issues. Willumsen (2018) presents several compelling economic challenges that autonomous maritime ships will have to overcome, including higher insurance costs due

 http://doi.org/10.24868/issn.2515-818X.2018.002

to the uncertainty of the new systems and the higher cost of redundant systems, many of which require higher cost fuels like Marine Diesel Oil or Marine Gas Oil instead of the much cheaper Heavy Fuel Oil. Kobyliński (2018) discusses operational barriers that may prevent adoption of autonomous maritime ships, such as those related to safety, security, environmental protection, political and human relations. In particular, he describes situations at sea that are generally 'impossible to forecast' such as Tsunamis, 'Freak Waves' and security breaches from pirates or other nefarious actors.

While this interest is palpable, the commercial adoption of autonomous maritime systems may be lagging behind the adoption of other types of autonomous systems: autonomous aircraft, 'self-driving' cars and autonomous spacecraft. This paper will explore the challenges and technological solutions that are common between autonomous maritime systems and other transport modes and the potential benefits to be gained from leveraging non-maritime developments in autonomy to be applied to maritime systems.

2. A Brief history of Non-Maritime Autonomous Systems

The improvement of sensor, control, computing and information technologies has led to the increased development of many different kinds of autonomous systems in recent years, however, developments toward unmanned and autonomous transport modes are far from new. This section provides a short history of several autonomous transport modes.

2.1. Autonomous Automobiles

Perhaps the autonomous vehicle with the most interest is the 'driverless' car, due to the near ubiquitous nature of automobiles in everyday life. While gaining much traction in recent years, experiments with autonomous automobiles are nearly a century old, with the first attempt in 1926 with the Linriccan wonder, an unsightly radio-controlled car that drove unmanned through New York City during a traffic jam (Bimbraw, 2015). Since then there have been many exploratory tests of self-driving cars including at the 1939 world's fair where General Motors sponsored a car that was fully guided by magnets implanted the road (Bel Geddes, 1940) all the way to 2015 when Tesla motors began offering a semi-autonomous feature for its cars called 'autopilot' (White, 2014).

2.2. Autonomous Aircraft

Autonomous aircraft have been around almost as long as their manned counterparts, with the first successful unmanned flight taking place in 1911, directed by Elmer Sperry, the inventor of the gyroscope and a contributor to maritime control as well. A large number of tests with unmanned aircraft continued until the 1920s when the commercial manned aviation industry greatly expanded and created the need for the federal air management system. Afterwards, most of the developments of wholly unmanned aircraft were performed by the military and focused on weapon delivery and using outdated aircraft as targets (Keane and Carr, 2013). Clearly this trend continues to the modern day where nearly all autonomous airplanes are operated by the military. In the meantime, considerable advancements in flying aids (i.e. autopilot) have been made in the commercial aircraft sector and small unmanned 'drones' have seen massive adoption in the private sector for entertainment and commercial purposes (Oppelt, 1976; Floreano and Wood, 2014).

2.3. Autonomous Space Systems

Space systems are somewhat unique in that they were developed to be autonomous first, later adding the capability to bring men into space. Today the vast majority of space systems are autonomous or unmanned as the costs for manned missions are much higher than unmanned (Gat, 1996). The continuing trend of lower cost access to space and increased demand for satellites and other space assets will continue to progress the development of autonomous space systems.

3. Common Technological Areas for Autonomous Systems

While each of the transport modes has its own unique purpose, many share common challenges and technologies, this section provides an overview of commonalities between autonomous systems. Inherent in all of the autonomous systems are many challenges, which involve technical, operational, legal, and economic aspects. The scope of this paper will be limited to three key technical areas that cross-cut all of the aforementioned autonomous systems: autonomous navigation and control, electrical energy propulsion, and remote communication. This list is certainly not exhaustive, but does represent important challenges that have not yet

 http://doi.org/10.24868/issn.2515-818X.2018.002

been covered across multiple autonomous transport modes. Examples of other important challenges in autonomous systems that have been covered previously include cybersecurity, which is covered in great detail by Yağdereli et al (2015) and the legal frameworks of autonomy, covered by Gogarty and Robinson (2011).

Autonomous navigation and control handles the capabilities of the autonomous system to have a situational awareness of both the static and dynamic conditions surrounding the vessel and thus allows the vessel to react appropriately. Navigation requires technologies such as GPS or other position sensing devices as described in Table 1. On board controls on the other hand, that allow appropriate reactions, are all based on internal system communication that do not necessarily require full autonomy on board, but could also be administered through instructions provided from shore, which would then require extremely secure linkages, similar to those present in spacecraft control. This second part of the technical area requires an in depth understanding of all on-board tasks and the communication internal to the ship.

Electrical energy propulsion is concerned with the means and technologies to create and convert energy that is fed towards auxiliary devices on board or turned into mechanical motion for the propulsion systems. While alternative energy storage methods are not a strict requirement for autonomous systems they are often associated very closely with autonomy due to expected decreases in complexity and moving components, thereby leading the way toward minimal/zero maintenance systems that exhibit graceful degradation (Zivi, 2004; Benson, 2013). Developments in electrical energy propulsions may also provide future vessels with greener energy which will play a role in keeping the maritime industry competitive with other modes of transport.

Finally, remote communication involves aspects of the autonomous system sending and receiving data to/from beyond-line-of-sight locations. The communication systems need to be able to deal with ship to ship communications, both with other autonomous vessels and amongst vessels that are still manned and therefore may appear unpredictable to the computer systems. Hence the communication development needs to mature to bridge the transition stages between fully manned and fully autonomous maritime vessels. This area is of course also concerned with data transmission of systems on board that are needed to provide monitoring capabilities to shore based stations, that will allow safe conduct and fast reactions in emergency situations. Topics such as data transmission speed, bandwidth and security are of main relevance in this field. Table 1 below provides a brief description of how each technical area is manifested in each transport domain.

Table 1: Example Embodiment of each Technology applied to each Transport Mode

	MARITIME	AUTOMOBILE	AEROSPACE	SPACE
NAVIGATION AND CONTROL	With integrated navigational sensors e.g. GPS, navigation radar and video cameras, the USV can conduct harbour surveillance even in busy waterways. The USV has the ability to provide remote detection, interrogation and engagement of potential threats to merchant vessels or naval ships. (Yan et al, 2010)	Operating a vehicle on public roads is complex due to the frequency of interactions with other, often-unpredictable objects including vehicles, pedestrians, cyclists, animals and potholes. (Litman, 2018)	Modern, large aircraft have been using automatic landing systems for years. Major airports such as Paris–Charles de Gaulle Airport are allowing only auto-landing aircraft, and in this way they remain operational for almost every day of the year (Yağdereli et al, 2015)	Attitude and articulation control (AACS), which is responsible for keeping the spacecraft (and its articulated components, if any) pointed in the right direction. … AACS includes a computer, attitude sensors (star trackers, sun sensors, gyros, etc.), accelerometers, attitude control devices (thrusters, reaction wheels, engine gimbals), and their associated control electronics and communications busses. (Gat, 1996)

http://doi.org/10.24868/issn.2515-818X.2018.002

ELECTRIC PROPULSION	These dynamically interdependent systems require dependable, fault-tolerant control to efficiently manage limited resources and to respond to casualty conditions" "common electric power system for real-time power allocation, re-configurability, and superior survivability" (Zivi, 2005)	Especially in the small vehicle segment, the model results (not shown here) predict that electrically propelled vehicles have significantly lower M&R-costs. Due to the significantly reduced complexity of the drivetrain (Propfe et al, 2012)	The multiple motors in the control surface provide inherent redundancy and graceful degradation. If the fatigue life of the motor turns out to be substantially lower than the aircraft design life, it should be possible to design the entire smart control surface to be a line replaceable item (Kudva, 2004)	Electrical power is almost always a scarce resource and must be carefully managed. If too much load is presented to the power source the voltage will drop to the point where the spacecraft computers can no longer operate. Most spacecraft power busses include a circuit breaker that shuts off all but essential systems in the event of low voltage, an event known as a bus trip. A bus trip happening at the wrong time can result in loss of the mission. (Gat, 1996)
REMOTE COMMUNICATION	A USV's position at the air–sea interface allows them to relay radio frequency transmissions in air and acoustic transmissions undersea. Thus, they are a key piece in the vision of the networked battle space of the US Navy. (Yağdereli et al, 2015)	Wirelesses networking among the vehicles and in the vehicle itself come in two forms: inter-vehicle networking around the vicinity of the vehicle, in the local area, known as vehicle to vehicle (V2V); and networking between a vehicle and its infrastructure system, known as vehicle to infrastructure (V2I) (Yağdereli et al, 2015)	Long-range wireless environment and satellite communications have been used for control and data transfer, communication data links have to be secured (Yağdereli et al, 2015)	A spacecraft is a completely self-contained artifact consisting of a number of subsystems, including communications, which includes the spacecraft's antennas and radio power amplifiers and receivers. (Gat, 1996)

 http://doi.org/10.24868/issn.2515-818X.2018.002

4. Patents to represent Each Technological Area in Each System

Within each of these technical areas many different technologies and implementations are being continuously explored by a large number of scientists, engineers and operators looking to help determine the dominant designs of the future autonomous transport modes.

4.1. Patent Classes to Represent Each Technical Area and Transport Mode

One way to capture this incredibly large set of technical developments and their impact on how each domain is changing over time is to use patents as a representation of technical progress (Trajtenberg, 1990; Benson, 2014). Using an objective and repeatable patent class searching method called the 'Classification Overlap Method', it is possible to determine a set of patents that represents each technological area as it is applied to each transport mode (Benson and Magee, 2013; 2015). For each technical area and each transport mode, a set of patent classes is selected to represent the overall technical developments. Table 2 below describes the patent class sets for each of the technical areas and transport modes.

Table 2: Patent Classes to Represent Each Technology Area and Transport Mode

	INTERNATIONAL PATENT CLASS (IPC)	**US PATENT CLASS (UPC)**
NAVIGATION AND CONTROL	G01C – Navigation G01S – Radio Navigation	73 – Measuring & Testing 701 – Navigation Data
ELECTRIC PROPULSION	H02K – Electric Machines H02P – Electric Motors H01M – Conversion to electrical energy	310 – Electrical Motors 318 – Electric Motive Systems 320 – Battery Discharging 429 – Chemical Energy
REMOTE COMMUNICATION	H04 – Electric Communication	455 – Telecommunications 340 – Communications: electrical
MARITIME	B63B – Waterborne Vessels	114 – Ships 440 – Marine Propulsion
AUTOMOBILE	B60 - Vehicles	180 – Motor Vehicles 280 – Land Vehicles
AEROSPACE	B64 – Aircraft, Aviation excluding B64G	244 – Aeronautics excluding 244/158
SPACE	B64G - Cosmonautics	244/158 - Spacecraft

4.2. Patent Sets to Represent the Technical Improvements in each Transport Mode

In order to find the technical inventions that are related to a specific transport-mode, the overlap between the two sets of patent classes provides the representative set of patents that are specific to that technical area and that transport mode. For example, the maritime remote communication patent set is defined as all of the patents that are found both (i.e. the overlap) in the remote communication set (H04M AND (455 OR 340)) and the maritime patent set (B63B OR 114 OR 440). Table 3 shows the number of patents for each technological area as they are applied to each transport mode. For example, there are 198 electric propulsion patents that are specifically focused on Aerospace, whereas there are 61 electric propulsion patents specifically focused on space-based applications.

 http://doi.org/10.24868/issn.2515-818X.2018.002

Table 3: Number of Patents Representing each Technology as applied to each Transport Mode

	MARITIME	AUTOMOBILE	AEROSPACE	SPACE
NAVIGATION AND CONTROL	122	2039	1181	188
ELECTRIC PROPULSION	126	5525	198	61
REMOTE COMMUNICATION	49	2360	246	132

4.3. Using Patents to Estimate Transport-mode Specific Technological Improvement Rates

While the simple number of patents is an interesting measure, it is a poor predictor of the rate of technological change. A measure of technological improvement based on patent meta-data can be used to estimate the technological growth rate of a specific technical domain similar to that of 'Moore's Law' (Benson and Magee, 2015). For this study only US patents issued after 1976 were analysed, due to unreliable meta-data associated with pre-1976 US patents. Table 4 shows the estimated technological improvement rates for each of the technical domains as they are applied to a specific transport mode.

Table 4: Estimated Technological Improvement Rates for each Technology as applied to each Transport Mode

	MARITIME	AUTOMOBILE	AEROSPACE	SPACE
NAVIGATION AND CONTROL	12%	131%	63%	55%
ELECTRIC PROPULSION	21%	47%	41%	21%
REMOTE COMMUNICATION	40%	110%	96%	93%

The improvement rates directly related to the maritime field are much lower than the improvement rates of the technical areas related to the other transport modes. The automotive transport mode has shown the highest improvement rates in each of the domains, with space and aerospace not far behind. The main outlier in the graph is the incredibly high improvement rate for automobile navigation, one potential explanation for this is the intense focus of the GPS and mapping industry with its focal point on automobile navigation.

5. Relationship of Technical Improvement Rates to Operational Cost

In order to better understand the impact these technical improvement rates may have on the actual operations of a transport mode, they must be applied to a meaningful operational metric. Freight shipping, the largest industry in the maritime domain, is used as the example case. One of the key metrics in the maritime shipping industry is the cost per weight-distance ($/(ton*km). The maritime shipping industry has historically improved this metric at ~2.1% per year (Hummels, 2007), which will set the baseline for comparison. The main contributing factors to this overall cost of freight shipping over its lifetime are fuel costs (12% of total costs), manning costs (37%), maintenance costs (15%) (Heckenberg, 2017). Each of these cost categories promises to be improved (reduced) by one or more of the technical areas.

In general, improvement in the navigation and control will decrease the manning costs, related to the bridge crew and the deckhands that help gain added situational awareness during manoeuvres, by means of improved 'autopilot' on board. Additionally, such technology can also reduce the amount of external services a vessel may need, for example, removing the need for a pilot to provide its support when sailing though challenging waters. This is similar to what happened in the commercial airline industry as autopilot developed and the required number of fully trained pilots was reduced from three to two on some routes.

Electric propulsion directly impacts the fuel consumption costs. The fuel consumption costs are due to more stable and potentially lower costs of electricity than their fossil fuel energy counterparts. The potential for increased efficiency due to electric propulsion will also decrease the need for total energy usage. This is similar to the case

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of electric automobiles, where the cost of fuel for electric vehicles is often significantly lower than their internal-combustion alternatives. An added benefit of the alternative fuels that also needs to be kept in mind since it will reach even more importance in the future is the fact that many of their energy options are providing a smaller environmental footprint than the fossil fuel options currently used.

Electric propulsion technologies also have the potential to lower maintenance costs due to fewer moving parts and thus reduced complexity and increased mean times between failure. This can come about through battery powered ships or fuel cell powered ships, but either way the promise is of a significantly reduced maintenance footprint. Another significant opportunity to improve the maintainability of ships is the ability of electrically propelled ships to exhibit 'graceful degradation'. Graceful degradation means that even if there is a failure on the ship, it is less likely to be critical, thus allowing for the ship to continue operations. This allows for higher risk tolerance of maintenance actions and thus reduced preventative and overall maintenance. The lower maintenance requirement is directly liked to also lowering the manning costs since fewer engineers are needed to look after the machinery. Spacecraft are generally powered through electrical elements and often exhibit very high availability and are usually designed with graceful degradation as a core principle, albeit at a high initial cost.

Remote communication also has the potential to generally decrease overall manning costs through the ability to move many of the monitoring and control functions from ship to shore, thus increasing the throughput for an individual captain who may be able to command many ships at once. This concept has already been applied in some situations with remotely controlled aircraft in the military, where a team can manage more than one remote-piloted-aircraft at one time from thousands of miles away.

Maritime-specific numbers are used to derive the quantitative relationship between technical improvements and operational improvement in the maritime industry. This relationship is then combined with the technical improvement rates from across all domains to estimate the potential increase in overall operational improvement to be gained from leveraging technical developments outside of the maritime field.

5.1. Base Case Scenario – 'Tunnel Vision' – Using only advancements in the Maritime Field

For the base case, only the improvement rates of the maritime specific technologies as listed in Table 4 will be used for the derivation of the relationship between technical improvement and operational improvement in the maritime field. As an admittedly simple assumption, the ratio between technical improvement and operational improvement is constant across the technical regimes, and the known overall historical rates of improvement and distribution of operational costs is used to solve for that constant as is shown in equation 1.

Equation 1:

$$OperImprRate_{Hist} = (TIR_{Nav} + TIR_{Comm}) * c * \%OpCost_{Man} + TIR_{Elec} * c * (\%OpCost_{Energy} + \%OpCost_{MX})$$

Where $OperImprRate_{Hist}$ = 2.1%, TIR_{Nav} = 12%, TIR_{Elec}=21%, TIR_{Comm} = 40%, $\%OpCost_{Man}$ = 37%, $\%OpCost_{Energy}$ = 12%, $\%OpCost_{MX}$ = 15%. Thus the assumed constant, c, is 0.085.

5.2. Accelerated Case – Standing on the shoulders of Giants – Leveraging Developments in All Fields

The second scenario uses the same relationship between maritime technical and operational improvement, but this time, will rely on the mean technological improvement rates across all transport modes for each technical area as were derived in 4.3: TIR_{Nav}=65%, TIR_{Elec}=33%, TIR_{Comm}=85%. Using Equation 1 with c = 0.085, the average technical improvement rates from all transport modes and the maritime distribution of operational costs results in an operational improvement rate of 5.5% per year.

5.3. Comparison of the Cases: Timing of Autonomous Maritime Systems Adoption

We compare the operational cost distributions of ocean vessels and their autonomous counterparts for a freight of 50,000 tonnes transported over a distance of 10,000km. As the data is historical, the 2004 USD is adjusted using the Purchasing Power Parity (PPP) (OECD, 2018). This is then converted to 2017 USD/tonne using the Consumer Purchasing Index (CPI) (BLS, 2018).

The operational costs are reduced by 2.1% per year for the base case and 5.5% per annum for the autonomous counterpart respectively. The initial cost of autonomous shipping is taken to be 1.26 times that of their non-autonomous counterparts (Kretschmann, 2015). From this, it is possible to estimate the timeframe of adoption of autonomous shipping when leveraging the technological developments of other transport modes using a Monte-Carlo Markov-Chain (MCMC) model, details of which can be found in Benson et al (2018).

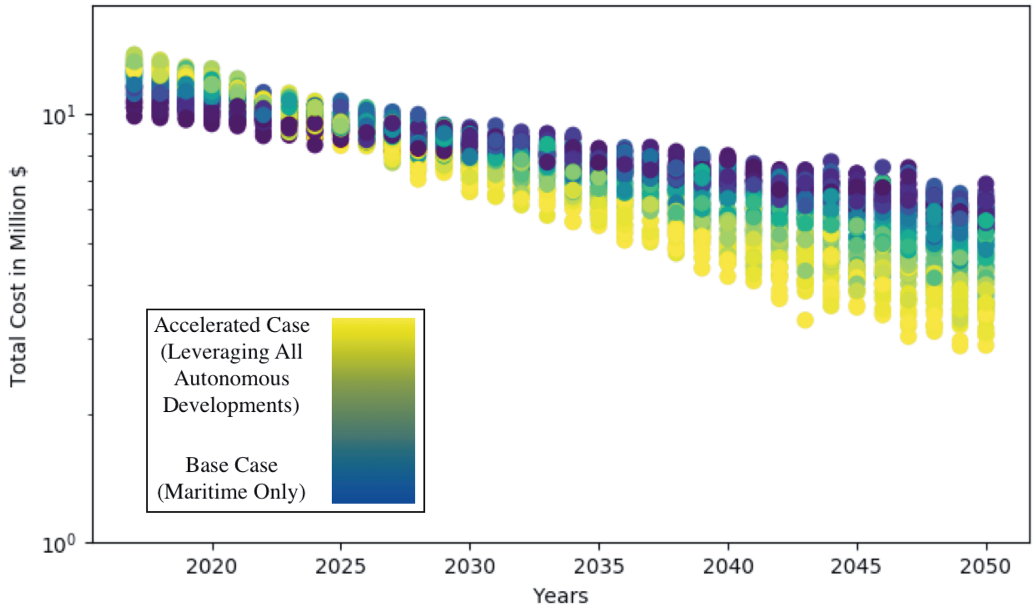

Figure 1: Operational Cost Distribution of Maritime-Only Vs All-Domain Autonomous Development

As is shown in Figure 1, the base case improvement (blue) starts out as more economically attractive, but is overtaken by the accelerated case (yellow) by 2028. This date is an indication of when autonomous maritime technologies may start to become technologically feasible.

6. Discussion and Conclusions

This study presents an overview of the developments of four of the most prominent modes of autonomous transport, specifically focusing on three different technical focus areas that these modes have in common. Specific embodiments of these technical areas are given for each of the transport modes to provide context to the common challenges. A set of patents for each technical area-transport mode pair is selected to provide a representation of the many technical developments that have occurred in autonomous systems. These patent sets are then analysed to give an estimate of the technological improvement rate for each of the three technical areas as they are applied to each of the transport modes. The results indicate that the developments in autonomy are lower across all three technical areas as they are applied to the maritime domain than the other transport modes. To provide an example of the impact of these differing technical improvement rates, they are correlated with historical maritime shipping operational improvement rates and the average cross-modal technological improvement rates are then used to calculate the change in estimated improvement rate if developments outside of the maritime field are used. This shows a potential increase in operational improvement rate of from 2.1% to 5.5%. Finally, these different numbers are compared using a Monte-Carl Markov Chain model to estimate the timing of adoption of autonomous maritime technologies to start around 2028 if intra-modal developments are leveraged.

The results indicate a strong incentive for the maritime industry to leverage outside developments as they can be applied to ships. This concept is certainly not new, and is in agreement with the seminal work on technology 'spill over' by Rosenberg (1982), but often it is easier to discuss this in theory than it is to accomplish it in practice. This paper itself provides a starting point for beginning to leverage the developments in other areas, simply by exploring and reading the patents and their related scientific work (many patents cite scientific journal articles). Another way of implementing this concept is to look to develop people who have deep multi-disciplinary experience (in this case multi-modal) as is recommended by Lau and Pasquini (2008). Implementation concepts themselves can be leveraged as well, as demonstrated by Theunissen (2014) with the cross-over of aircraft flight management systems to the maritime industry. Finally, one other way of implementing such recommendations could simply be reframing the problem from being one where autonomous maritime is the art of making a ship able to sense and react to its surrounding, to instead making a smart robot able to float and withstand the unique conditions of the sea (Dorst, 2010).

Compared to other modes of transport, maritime vessels are some of the largest and most complex systems. They are designed and built to operate reliably for several decades while withstanding the challenges thrown by the sea. Thus, all of the focus on looking to other domains for inspiration cannot remove the critically important task of deeply understanding the domain specific challenges present in propulsion, communication, navigation & control for maritime vessels. Maritime designers and engineers must deal with harsh and unique environments presented by water and the sea, such as salt, corrosion, and intense weather and sea conditions. Remote operating locations mean that help may be days away from a broken down vessel, thus requiring an accordingly robust and reliable design. One other aspect that must not be forgotten is that of all the transport modes, maritime is the oldest, and thus carries significant history and is built upon millennia of technological developments to get to where we are today. When looking to build upon that legacy, it is important to stand on not only the shoulders of giants from other domains, but the countless maritime giants of yesterday and today.

7. Acknowledgements

The author would like to thank TU Delft, the National Netherlands Defence Academy and the US Air Force for contributing to this research. The views expressed in this paper are that of the authors and do not necessarily represent the views and opinions of the US Air Force.

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