Unmanned and Autonomous Ships

An Overview of MASS

R. Glenn Wright

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To Magdalena …

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Preface

Unmanned and autonomous ships are quickly becoming a reality in an effort to make shipping safer and more efficient. However, traditional lines based upon function and scale become blurred as new technology changes how the unique needs of different sectors are met. In addition to large vessels dedicated to the transport of goods and cargos across the oceans, major efforts are underway towards automation of small coastal shipping that includes ferries, tugboats, supply and service vessels, and barges. Further innovation is taking place in automated vessels replacing conventional ships for inspecting and servicing pipelines, drilling platforms, wind farms and other offshore installations. Tasks that have in the past been performed by large ships are planned to be accomplished by much smaller vessels, surface and undersea vehicles designed for specific purposes. Innovations in hydrodynamics and aerodynamics are leading to the development of unmanned automated hybrid vessels that appear to be a cross between ships and airplanes, sharing the advantages and disadvantages of both.

The segment of unmanned and automated ships within the responsibilities of both nation states and the International Maritime Organization (IMO) is considered in this book and, specifically, Maritime Autonomous Surface Ship (MASS) operations that may be addressed by existing and future IMO instruments as adopted and implemented in national regulations. The subject is introduced in Chapter 1 by providing a historical perspective on shipping and framing current initiatives in terms of ship, technology and test bed development within this context. In Chapter 2 automated shipping is explored in terms of economics, technology, safety and the environment. Chapters 3 through 8 discuss details of autonomy and automation, ship design and engineering, command and control, navigation, communications, training and security as pertain specifically to this unique segment of the shipping industry. Chapter 10 is dedicated to describing regulatory issues at the international level, among nation states, classification societies and non-governmental organizations and in Chapter 11 there is a discussion of the legal instruments and issues that have been considered with regard to automated maritime operations. Finally, in Chapter 12 future short- and long-term directions for unmanned and autonomous shipping are described, including predictions for civilian adoption of military ship automation programs, new trends in instrumentation and recommendations as to how mariners, industry and governments can enhance the opportunities presented through the adoption of these technologies.

This book is aimed at mariners, ship owners and operators, regulatory authorities, protection and indemnity insurance clubs, environmental groups and others interested in maritime affairs. Others with interest include undergraduate students involved in deck officer training, graduate students and academics involved in research pertaining to ship design, navigation and environmental studies.

Acronyms and Abbreviations

ABS	American Bureau of Shipping
ACTUV	Anti-submarine warfare Continuous Trail Unmanned Vessel
AMOS	NTNU Center for Autonomous Operations and Services
AI	Artificial Intelligence
AIS	Automated Identification System
AIS-ATON	AIS (radio-based) ATON
ARPA	Automatic Radar Plotting Aid
ASDS	Autonomous Spaceport Drone Ship
ATON	Aid to Navigation
BeiDou	Navigation Satellite System (China)
BIMCO	Baltic and International Maritime Council
BV	Bureau Veritas
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CCS	China Classification Society
Cefor	Nordic Association of Marine Insurers
CMI	Comité Maritime International
COLREGS	International Regulations for Preventing Collisions at Sea
CPA	Closest Point of Approach
CPU	Central Processing Unit
CSBWG	Crowd Sourced Bathymetry Working Group (International Hydrographic Organization)
CSO	Company Security Officer
DARPA	Defense Advanced Research Projects Agency (United States)
DMA	Danish Maritime Authority
DNV-GL	Det Norske Veritas/Germanischer Lloyd
DSC	Digital Select Calling
ECDIS	Electronic Chart Display Information System
eLoran	Enhanced Long Range Navigation system
ENC	Electronic Navigational Chart
FFI	Norwegian Defence Research Establishment
Galileo	Satellite Navigation System (European Union)

Gbps	Gigabits per second
GHz	Gigahertz
GLONASS	Globalnaya Navigazionnaya Sputnikovaya Sistema (Russia)
GMDSS	Global Maritime Distress and Safety System
GNSS	Global Navigation Satellite System GPS Global Positioning System (United States)
GPU	Graphical Processing Unit
IACS	International Association of Classification Societies Ltd
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
IBS	Integrated Bridge System
ICS	International Chamber of Shipping
IFSMA	International Federation of Shipmaster's Associations
IMarEST	Institute of Marine Engineering, Science and Technology
IMCA	International Marine Contracting Association
IMO	International Maritime Organization
INS	Integrated Navigation System
IoT	Internet of Things
ISO	International Organization for Standardization
ISMFA	International Federation of Shipmasters' Associations
ISO	International Organization for Standardization
ITF	International Transport Workers' Federation kHz kilohertz
KR	Korean Register of Shipping
LEO	Low Earth Orbit
Lidar	Light Imaging Detection and Ranging
LNG	Liquefied Natural Gas
Loran	Long Range Navigation system
LL	International Convention of Load Lines
LR	Lloyd's Register of Shipping
LRIT	Long Range Identification and Tracking
MARINTEK	Norwegian Marine Technology Research Institute
MARPOL	International Convention for the Prevention of Pollution from Ships
MARSEC	Maritime Security
MASS	Maritime Autonomous Surface Ships
Mbps	Megabits per second
METOC	Meteorological and Oceanographic
MHz	Megahertz
MSC	Maritime Safety Committee (IMO)
MSI	Maritime Safety Information
MUNIN	Maritime Unmanned Navigation through Intelligence in Networks
NCA	Coastal Administration

NGO	Non-Governmental Organization
NFAS	Norwegian Forum for Autonomous Ships
NI	Nautical Institute
NMA	Norwegian Maritime Authority
NOAA	National Oceanographic and Atmospheric Administration (United States)
NPU	Neural Processing Unit
NTNU	Norwegian University of Science and Technology
OPU	Optimizing Processing Unit
OOW	Officer of the Watch
PXI	PCI eXtensions for Instrumentation
RACON	Radar Beacon
Radar	Radio Detection and Ranging
RCC	Remote Control Center
SAE	Society of Automotive Engineers
SAR	Search and Rescue
SOLAS	International Convention for the Safety of Life at Sea
Sonar	Sound Navigation and Ranging
SSC	Smart Ships Coalition
STCW	International Convention on Standards of Training, Certification and Watchkeeping
UAV	Unmanned Aerial Vehicle
UCSDA	Unmanned Cargo Ship Development Alliance
USV	Unmanned Surface Vehicle
UUV	Unmanned Underwater Vehicle
VATON	Virtual Aid to Navigation
VSO	Vessel Security Officer
VSP	Vessel Security Plan
VTS	Vessel Traffic Services
WAN	Wide Area Network

Chapter 1

Introduction

This book examines unmanned and autonomous shipping within the context of key design elements and systems necessary to accomplish multiple levels of automation. We begin with this chapter by providing relevant history and cite examples of present-day developments along with some topics of concern voiced by mariners. Subsequent chapters examine the future of maritime shipping and its impact on trade, national economies, technological advancement and the seafarers who have bravely pursued their trades over the centuries. Automation is being accomplished across all levels of shipping from the smallest recreational boats to the largest oil tankers, container ships, cargo carriers and cruise ships. While the contents of this book generally apply to vessels of all sizes and types supporting diverse functions and purposes, its goal is to examine the issues associated with larger surface vessels and their support craft that are operated by professional captains, mates, crews and pilots. No attempt is made to address issues associated with small drones, more commonly referred to as unmanned or autonomous surface vehicles (USVs/ASVs), except as they may be utilized by large vessels, even though there may be great commonality in the technical details of their implementation.

A question exists of whether unmanned and autonomous ships represent the next step in the logical evolution of shipping and ship technology or if they exemplify disruptive innovation that will completely transform the face of maritime shipping as we know it. Although there are vested interests promoting both scenarios, rapid change generally does not occur in the shipping industry and there is no reason to believe that present-day masters and crews are destined for early retirement. Maritime jobs continue to be influenced by changes in technology and economies and few would or even should take the time to argue over the virtues of oar versus sail, steam versus gas turbine, or nuclear versus liquefied natural gas (LNG) or hydrogen fuel cell propulsion. Some of these technologies are relegated to the past while others represent possible alternatives for the future. In the meantime, it is hoped this book can draw attention to the present state of events and activities surrounding the furtherance of what the International Maritime Organization (IMO) refers to as Maritime Autonomous Surface Ships

(MASS). Readers may then decide for themselves as to what the future may hold and what influence they have had.

1.1 A HISTORICAL PERSPECTIVE ON ADVANCES IN SHIPPING

There are certain events considered key milestones in the development of ships and shipping technology that were hallmarks of change. Sails harnessed the wind to propel ships across vast distances, while oars provided a means of propulsion that made vessels more maneuverable and could be depended upon when the wind was unreliable. Iron ships eventually replaced wooden ships, and steam power replaced sails in general but wind-powered ships using new technologies are still being actively developed. These changes occurred gradually with iron being used initially to connect fasteners and strengthen hulls decades before the appearance of the first iron ships. However, new technology also introduced new problems. One example is how iron ships adversely affected the operation of magnetic compasses. Through the experimentation of astronomer Sir George Biddell Airy in 1839, this problem was solved with his development of correction tables that were subsequently adopted by the Merchant and Royal Navies in England and spread throughout the rest of the world [Airy 1839; Wright 1988]. Such innovations originated from a broad cross-section of people and professions including naval architects as well as inventors, practical tradesmen and scientists, many of whom were not mariners, shipbuilders, or even seafarers. Nevertheless, their discoveries and inventions changed the face of shipping, opened up worldwide trade routes and set the stage for exploration and mass migration on a large scale. Today, similar advances are being made by engineers, metallurgists, chemists, computer scientists and others that may have never set foot on the deck of a ship. Yet, their contributions in the development of new electronic control and guidance systems along with the software through which they operate are essential for today's ships. The introduction of new technology to aid in vessel communication, navigation and overall situational awareness is summarized by the timeline shown in Figure 1.1. The timeline is not to scale and many of the dates given are approximations as conflicting dates and claims are often present in the literature. However, it provides a good illustration of how developments have accelerated during recent times in four primary disciplines: Construction, propulsion, navigation and communications. The convergence of many aspects of these four disciplines in the modern era has ultimately lead to the present day where the concept of MASS can now be entertained through the establishment of automated command and control over all of the systems needed to operate the vessel and therefore the entire vessel itself.

The following paragraphs provide brief descriptions of new developments in technology and ship function that have taken place relatively

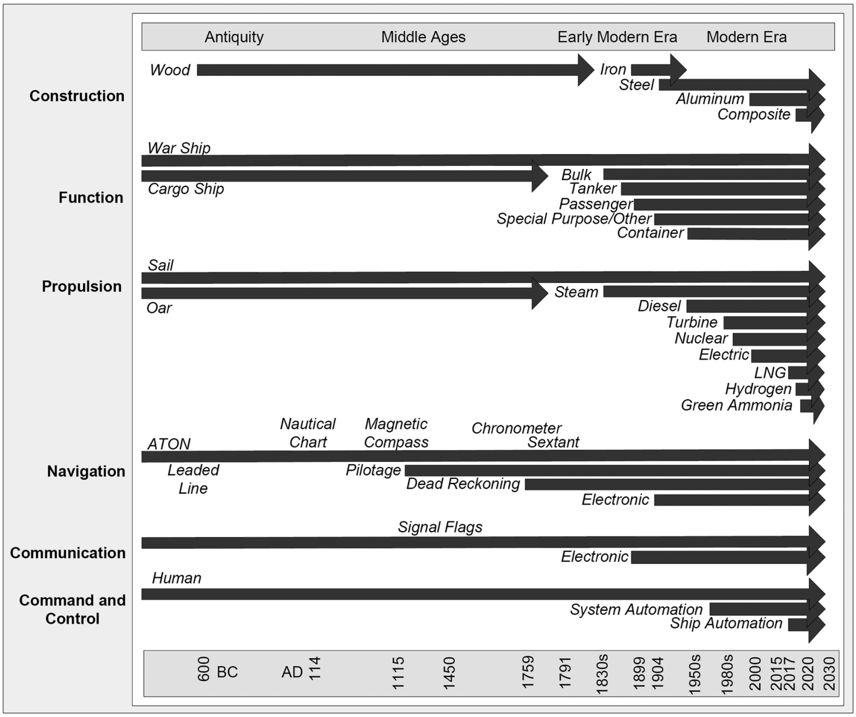

Figure 1.1 Timeline of new technology introduction on ships.

independently of each other, yet are essential components to achieve vessel autonomy. The common denominator in modern times among these disciplines is the advent of computer-aided design and simulation of all aspects of ship construction and performance combined with electrical and electronic control of all major ship propulsion, navigation and communications systems.

1.1.1 Construction

Wood floats, and it was a natural progression to build log canoes to large sailing vessels from this material. Towards the late 1700s iron plates began to appear on inland barges, in part out of necessity due to shortages of lumber [Walker 2010]. Ships with hulls made of iron started to appear in 1818, when the iron barge *Vulcan* was built near Glasgow, Scotland. Overcoming prejudices and concerns among early seafarers as to whether iron ships could actually float was a key inhibitor of early progress [Benson 1923]. Once new processes were developed for manufacturing steel and it became available in sufficient quantities (i.e., tons), large plates of various thicknesses were used to build ships of steel. Improvements in riveting and welding helped to increase vessel size from the 5,000-ton ships of the 1880s to the 250,000-plus-ton ships that are commonplace today. In some cases, attempts have been successful in creating hulls using aluminum. However, difficulties related to welding and galvanic corrosion, especially where a steel shaft passes through the hull, reduce reliability and impose greater maintenance requirements. Carbon fiber composite materials providing lightweight and strong hull forms are presently being developed for smaller vessels but its use for large ships is yet to be realized due to the high costs involved in its production.

Of greatest significance to make possible automated ships are the revolutionary changes in modern era methods and processes used in their construction. As ships have increased in size the former methods of using curves, drawing frames and templates have given way to computer-aided design (CAD), computer-aided engineering (CAE) and computer-aided manufacturing (CAM), making it possible to visualize, evaluate and test design concepts long before the first metal is cut. This includes determining the types of onboard physical and virtual sensors necessary and their proper placement to assess ship performance. The outcome includes better processes that result in improved design and production times at less cost than would otherwise be possible.

1.1.2 Function

Ship designs originated to perform two distinct functions as warships and cargo ships, each with their own unique design features that made them suitable for their task. Cargo ships were also used to transport small numbers of passengers. As the use of sails gave way to steam propulsion, ships of different designs began to be developed for the transportation of inland freight and passengers. Cargo ships continued to develop to support more specialized cargos separating into bulk carriers, tankers and container ships in the 20th century. During this same period passenger ships, with and without cargo, also began to flourish from small river boats and passenger ferries, to great ocean liners and cruise ships designed for pleasure excursions. In the meantime, other specialized ships for fishing, offshore construction and support, drilling, cable laying and a myriad of other uses entered the scene. A broad cross-section of vessels performing these functions is the focus of many autonomy research and development efforts today.

1.1.3 Propulsion

Sails have been present on ships since antiquity and are historically the primary mode of ship propulsion up until modern times. Wind power provided by rotors and other inventions is still being considered for auxiliary ship propulsion. The use of paddles and oars has also complemented sail power. However, the advent of the steam engine heralded the modern age of ship propulsion. Early problems with steam engines and their lack of power were eventually overcome as experience and lessons learned in their use were acquired. However, other problems persisted. Robert Fulton's steamboat *Clermont*, otherwise known as Fulton's Folly, caused spectators to fear when the smoke, flames and steam of the engine made it appear about to explode [Sale 2017]. The 1900s found coal-fired boilers replaced with oil, and today steam has become obsolete and replaced by diesel and turbine power. Nuclear power was used on an experimental basis in the mid-1900s to power commercial ships. However, except for a few specialized ships such as icebreakers, its maritime use is generally relegated to warships. Today on many vessels large engines connected to propellers using drive shafts are being replaced with electric engines connected directly to a propeller enclosed in a steerable gondola or pod suspended below the hull. Liquefied natural gas (LNG) is appearing as a fuel of choice that provides much cleaner performance in terms of environmental emissions. Hydrogen and green ammonia are other potential clean fuel sources being considered for the future.

Just as significant as the types of engines and fuels used on board ships has been the evolution of automated engine and power monitoring and control systems that enable many ships to operate with reduced staffing requirements and unattended machinery spaces. These electronic systems can automatically monitor and control temperatures, pressures, flows, levels, torque and other characteristics of propulsion systems necessary for safe operation.

1.1.4 Navigation

Basic navigation capabilities have been achieved through the invention of the leaded line, nautical chart, compass, chronometer and sextant. The leaded line used to measure water depth was mentioned by Herodotus in the fifth century B.C. [Macaulay 1890]. Early marine charts can be traced back to Marinus of Tyre in the second century [Deetz 1943]. The compass was used for maritime navigation in China around the year 1115 [Ronan 1986]. The chronometer, used for obtaining precise timing information, became available in 1759 [Gould 1921]. The modern sextant had its origins around 1791 [Ifland 1998]. These inventions form the core instruments found in all modern ships. However, the use of electronic systems in the modern era has changed the face of ship navigation.

1.1.5 Communications

The primary method of communication between ships began in the 15th century with the appearance of systems of signal flags and pennants hoisted for communication [Sterling 2011]. These were eventually replaced in the

19th century with the advent of semaphore systems. Light signals were used at night and became more viable with the invention of the electric light bulb. Paralleling advances in navigation, communications by ships with land sites and between ships greatly improved with the invention of the wireless telegraph and other electrical and electronic systems.

1.1.6 Electronic Navigation and Communications

Although slow to occur at first, the pace of evolution of navigation and communications technology has dramatically accelerated beginning in the last century with the advent of electrical and electronic devices as illustrated in Table 1.1. The introduction of radio detection and ranging (Radar) equipment for shipboard use occurred in 1937 [Eagle 2008]. The effective use of Radar on ships was stymied by a lack of standards and training that eventually resulted in the first Radar-assisted collision between *Andrea Doria* and *Stockholm* [Meurn 2013]. Techniques were developed over the decades to plot range and bearings to stationary landmarks and buoys to establish position fixes for navigation, and to other ships as a means of collision avoidance. Radar beacon (RACON) transponders that reside on buoys and structures and emit a signal when interrogated by a Radar transmission were introduced in 1962 [ITU-R M.824-4]. In 1979, Automatic Radar Plotting Aid (ARPA) technology was introduced to acquire and track targets and automatically compute and display information to aid the bridge watch in collision risk assessment and collision avoidance [Hayashi et al. 1994].

Automated Identification System (AIS) was introduced in 2000 to automatically exchange static and dynamic ship information pertaining to the voyage, safety and security between vessels and to shore stations [Noris 2008]. AIS has also been introduced onto the Radar display whereby ship name, speed, heading and other information may be shown, aiding in target identification and providing a means to establish direct communications with specific vessels of interest to exchange passing and other information [Pillich and Schack 2002]. This was followed by the introduction of satellite AIS beginning in 2005 for the tracking of vessels at sea beyond the range of shore-based receivers [ESA 2009].

Electronic Chart Display Information System (ECDIS) is a navigation information system intended to display all chart information necessary for safe and efficient navigation originated by, and distributed on the authority of, government-authorized hydrographic offices [MSC 82/24]. With adequate back-up arrangements it may be accepted as complying with the Convention on the Safety of Life at Sea (SOLAS) up-to-date chart requirements [SOLAS 1974]. ECDIS provides access to the electronic equivalent of a paper chart for vessel navigation through the means of an electronic navigation chart (ENC) and system electronic navigation chart (SENC) comprised of database attributes used for display generation and navigation