



ESCOLA NAVAL



ta san tõe bife faire

David Luís dos Santos Castro

**PNT Resilience and the impact of satellite radio
positioning disruptions on piloting teams**
An experimental study using a navigation simulator

A dissertation submitted in partial fulfillment of
the requirements for the degree of Naval Military Sciences,
specialisation of Marinha



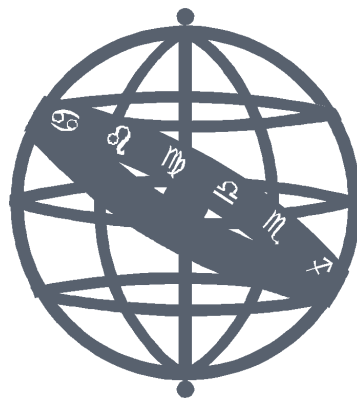
Alfeite

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talant de bi-faire



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Supervision of: CFR Vítor Fernando Plácido da Conceição

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Resumo

O sucesso nas operações marítimas apenas pode ser atingido através da interação eficiente e eficaz entre pessoas e tecnologia. Tendo em conta a crescente dependência na última a bordo dos navios, uma das questões mais prementes é a provada falibilidade dos sistemas de radioposicionamento satélite, nomeadamente dos GNSS (*Global Navigation Satellite Systems*) que, conseqüentemente, tem levantado preocupações relativamente à resiliência dos mesmos. Os requisitos das fontes de posicionamento, navegação e tempo (PNT) também têm crescido significativamente na última década, portanto, a qualidade e integridade desses três parâmetros tornaram-se cada vez mais um elemento decisivo para o sucesso nas operações marítimas, especialmente na condução da navegação. O objetivo do estudo é identificar quais os fatores de sucesso para uma navegação mais resiliente. A solução proposta passa portanto pela abordagem da resiliência PNT através dos Sistemas Cognitivos Conjuntos, medindo o desempenho das equipas, o cumprimento dos procedimentos e fatores humanos, nomeadamente a interação quer com a tecnologia, quer entre os diferentes membros da equipa, a confiança na automação, assim como o conhecimento situacional e a carga de trabalho, quando confrontados com uma disrupção GNSS. Os participantes do estudo foram equipas de pilotagem da Marinha Portuguesa (MP) e as sessões ocorreram num simulador de navegação. As equipas realizaram um treino de pilotagem padrão dividido em três momentos distintos: com normal disponibilidade de sinal GNSS, sob spoofing e sob jamming. O desempenho foi medido com base em medidas quantitativas de controlo do posicionamento e do tempo, o cumprimento dos procedimentos com o apoio de avaliadores do CITAN e os fatores humanos foram medidos sobretudo recorrendo a questionários. A metodologia FRAM (*Functional Resonance Analysis Method*) providenciou o suporte para analisar as diferenças entre o trabalho como prescrito e o trabalho como é realizado. O estudo pretende providenciar um conhecimento extensivo relativamente à capacidade das equipas de pilotagem em efetuarem a condução da navegação face à adversidade de uma disrupção GNSS, efetivamente elevando o nível de conhecimento da função PNT na MP e abrindo caminho para soluções de Sistemas Cognitivos Conjuntos para uma melhor e mais resiliente condução da navegação.

Palavras-chave: Segurança da navegação, Resiliência PNT, Fatores Humanos, Sistemas Cognitivos Conjuntos

Abstract

Success in maritime operations can only be achieved through efficient and effective interaction between people and technology. Given the growing dependency on the latter aboard ships, one of the most pressing issues is the proven fallibility of satellite radio positioning systems, namely GNSS (Global Navigation Satellite System), which have raised resilience concerns. The requirements for the position, navigation, and timing (PNT) sources have grown significantly over the past decade. So, the quality and integrity of those three parameters have become a more decisive element for success in maritime operations, especially navigation. Therefore, the proposed solution addresses the PNT resilience through the scope of Joint Cognitive Systems, measuring teams' performance, procedure compliance, and human factors. The latter includes interactions with technology and other team members, trust in automation, situational awareness, and workload when faced with a GNSS disruption. The study's participants were piloting teams from the Portuguese navy in a navigation simulator. The teams performed a simple piloting training split into three distinct moments: normal availability of GNSS signal, undergoing spoofing, and undergoing jamming. The performance was measured through quantitative measurements of time and positioning control and procedure compliance with the support of evaluators from CITAN. The human factors were primarily measured using questionnaires. The FRAM methodology (Functional Resonance Analysis Method) provided the support to analyze the differences between Work as Done and Work as Prescribed. The study intends to provide extensive insight into the piloting teams' ability to navigate in the face of the adversity of GNSS disruption, effectively upraising the knowledge of the PNT function in the Portuguese navy and paving the way to Joint Cognitive Systems solutions for a better, more resilient navigation.

Keywords: Maritime navigation safety, PNT Resilience, Human Factors, Joint Cognitive Systems

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List of Abbreviations

AGC	Automatic Gain Control
AIS	Automatic Identification System
ARPA	Automatic Radar Plotting Aid
ATA	Actual Time of Arrival
ATD	Actual Time of Departure
AtI	Aspects to Improve
AtON	Aid to Navigation
BRM	Bridge Resource Management
CSE	Cognitive Systems Engineering
DGPS	Differential Global Positioning System
DPB	Demographics and Professional Background
DoD	Department (of) Defense
EA	Electronic Attack
ECDIS	Electronic Chart Display and Information System
EP	Electronic Protection
ES	Electronic Support
ETA	Estimated Time of Arrival
ETD	Estimated Time of Departure
EW	Electronic Warfare
FRAM	Functional Resonance Analysis Method
GBAS	Ground Based Augmentation
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
ICT	Information and Communication Technologies
INEC	International Naval Engineering Conference
JCS	Joint Cognitive Systems
NATO	North (it) Atlantic Treaty Organization
NAVSIM	NAVigation SIMulator
NAVWAR	NAVigation WARfare
OST	Operational Sea Training
PILOTEx	PILoting EXercise

PNT	P osition N avigation T iming
PTC	P ortuguese T actical C enter
PVT	P osition V elocity T ime
SART	S ituational A wareness R ating T echnique
SA	S ituational A wareness
SBAS	S pace B ased A ugmentation S ystem
SBT	S imulation B ased T raining
SIMPILOTEX	S IMulated P ILoting E Xercise
VHF	V ery H igh F requency
WAD	W ork A s D one
WAP	W ork A s P rescribed
WL	W ork L oad

Introduction

Resilience has been a topic that has increasingly driven scientific research (Janssen et al., 2006). The world is increasingly volatile, especially because of the pace at which just about everything seems to change (Notteboom and Siu Lee Lam, 2014). The maritime industry is no exception. Some of the most used and relied upon technologies today aboard ships (civil or military ones) have been around for a relatively short time.

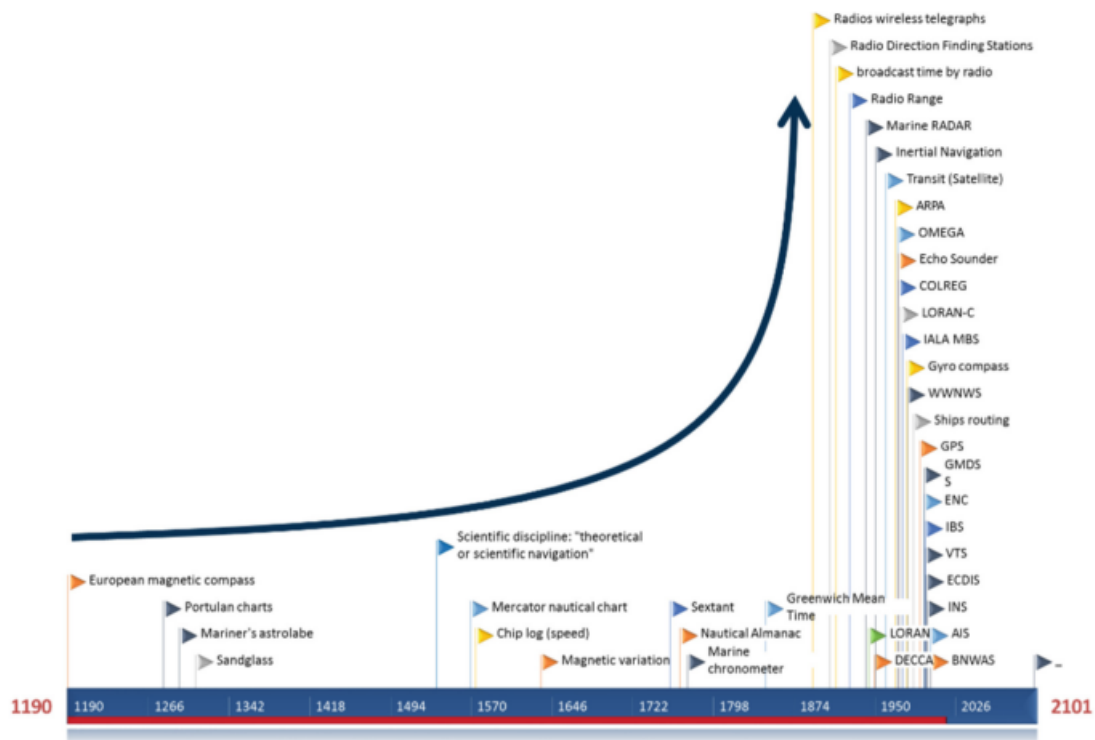


FIGURE 1: Past, present, and future maritime technologies and techniques. Source: Conceição et al (2018), p.3

Expanding this idea on the technology which the present study will tend to focus on: satellite radio positioning systems, GPS (Global Positioning System), the first of its kind, was introduced merely around 30 years ago and has been undergoing constant technology upgrades and changes both in the system itself and in other support systems such as DGPS (Differential GPS) technology (Batista, 2019). In

addition, there are now several other Global Navigation Satellite Systems (GNSS) operated by several other countries. This technology has deeply impacted maritime operations and is very much relied upon because of its accessibility and accuracy (GPS.gov, 2021a).

Unfortunately, the pace of change has not only been impacting the technology positively but has the potential to disrupt it. It is increasingly easier and cheaper to create disruptions to the GPS systems, and the system is relatively fragile to intentional and unintentional interferences. These interferences are due to its working principles, mainly the low power of its radio waves (Aresta, 2017), which can lead to cascading failures due to the large global dependency on GPS. Although these disruptions have not been frequent enough to drive the mass use of alternatives, they have been enough to raise both awareness and concern about the topic and the need for resilience of Position, Navigation, and Timing (PNT) (Oroliia, 2022).

The importance attributed to the issue is evidenced by the growing production of several papers and other relevant scientific work (Janssen et al., 2006). It has also been featured several times through different scopes in NATO (North Atlantic Treaty Organization) Review (Paulauskas, 2020). When it comes simply to the study of the impact of GPS jamming and spoofing in maritime navigation, this growing production is evidenced in the following figure.

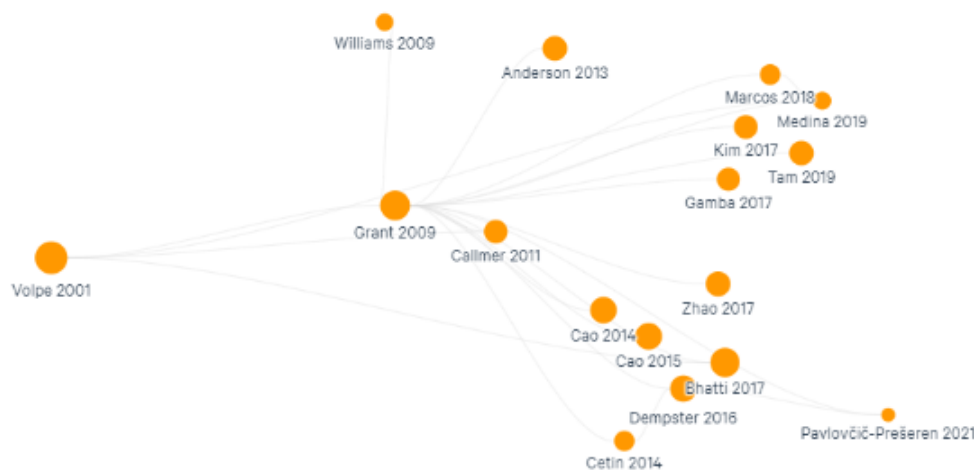


FIGURE 2: Papers on the topic of GPS jamming and spoofing in maritime navigation

In parallel, several work groups have been established, both civil and military, national and international, to tackle PNT resilience. Some examples are the new DoD (Department of Defense) Task Force "Position, Navigation and Timing Control" or the Exploratory Team "NATO PNT Open System Architecture and Standards to Ensure PNT in NAVWAR (Navigation Warfare) Environments" (Goward, 2020). NATO consistently identifies resilience as a priority, emphasizing the need to train to fail and anticipate disruptive challenges, acting to prevent or adapt to them (NATO, 2022).

Given the importance of PNT in its operations, the Portuguese navy is a prominent stakeholder and, therefore, should be a part of the global effort to uphold a higher standard of resilient navigation. Any ship of the Portuguese navy today is, to a bigger or lesser extent, dependent on a rigorous PNT reference for the well functioning of most of its systems (Aresta, 2017).

Therefore, it becomes essential that the institution seeks a deeper understanding of the real impact of the PNT systems and their possible shortcomings and vulnerabilities. This can be achieved by identifying solutions, improvements, and new steps toward resilience in NAVWAR scenarios for which a highly reliable, high readiness navy has to be prepared.

This work will attempt to contribute to this knowledge by studying the impact a GNSS disruption has on the piloting teams and their relationship with technology while performing a port entrance. The same scenario was played by all participating teams in a Navigation Simulator, starting with normal GNSS signal availability and then sequentially introducing a spoofing and jamming attack. As a piloting team combines technological and human resources, the study follows a Joint Cognitive Systems approach, measuring and analyzing the human-machine ensemble.

The main goal is to identify the success factors in overcoming a GNSS disruption. This is attained by looking at the teams' ability to control both positioning and tempo, analyzing the best and worse performing teams, and understanding what explains those performance differences. The study collects demographic and professional background data. It measures GNSS theoretical knowledge, trust from the operators in their respective equipment, Situational Awareness, Workload, and the interaction changes throughout the session (both with technology and between the different team members).

Teams' procedure compliance was also measured in two dimensions: generic

piloting procedures and post-disruption. These measurements were made through the processing of the data from the video and audio recordings, the bridge equipment logs, as well as questionnaires (GNSS-dependent equipments/systems form, Demographics and Professional Background Questionnaire, Trust in Automation Survey, SART, Expanded NASA-TLX), performance report from the navigation experts and action checklists. This is evidenced in the structure of chapters 3 and 4, which dedicates each section and subsection to each data category.

It is expected that by identifying the success factors for facing the adversity of a GNSS disruption, the study can provide extensive insight into teams' decision-making and how the human factors relate to resilience. In turn, this can give way to a new perspective and perhaps new ideas and improvements for a better, more resilient navigation and, therefore, a better, more resilient navy.

In terms of structure, the study is divided into four chapters. Chapter 1 begins with a brief explanation of the concept of PNT and the current state of the art in Satellite Radio Positioning Systems. It continues exploring the dangers and expansion of Electronic Warfare, the idea of Navigation Warfare, and the impact of GNSS disruption on maritime safety, one of the primary motivations for the study. The frameworks and methodologies relevant for such a study (involving teams operating with technology) are also explored, namely Joint Cognitive Systems, Resilience Engineering, and the varieties of work and their representations. The chapter ends with an explanation of the Portuguese navigation doctrine, piloting teams, and navigation training in the Portuguese navy.

Chapter 2 details the methodology used throughout the experiments in data collection and processing, mentioning the research questions, the study design, ethics, and the chosen measurements, finishing with some technological considerations and the limitations of the methodology and the study.

Chapter 3 focuses on results, describing the qualitative observations that were made and the piloting model built through the use of the Functional Resonance Analysis Method. It is also presented all the quantitative data collected (performance, procedure compliance, and all human factors measurements).

The last chapter describes the differences between work as prescribed and work as done in the experiments, accompanied by a reflection on how to close that gap. It continues with the analysis of the data presented in the previous chapter, interpreting it critically in comparison with previous findings while simultaneously providing the answers to the research questions. The study ends with presenting an

overall balance of the study, its main conclusions, and providing examples for future work.

Chapter 1

Literature Review

1.1 PNT and Satellite Radio Positioning Systems

PNT is the acronym for Position, Navigation, and Timing defined by the US Department of Transportation as:

"Positioning, the ability to accurately and precisely determine one's location and orientation two-dimensionally (or three-dimensionally when required) referenced to a standard geodetic system (such as World Geodetic System 1984, or WGS84); Navigation, the ability to determine current and desired position (relative or absolute) and apply corrections to course, orientation, and speed to attain a desired position anywhere around the world, from sub-surface to surface and from surface to space; and Timing, the ability to acquire and maintain accurate and precise time from a standard (Coordinated Universal Time, or UTC), anywhere in the world and within user-defined timeliness parameters" (US Department of Transportation, 2017).

The advent of sextants, machine-powered vessels, RADAR, and many other technological innovations have revolutionized the way navigation is conducted at sea (Batista, 2019). The same can be said about radio positioning systems, especially global satellite radio positioning systems.

Even though there are multiple PNT sources, as illustrated in the figure below, these systems are now the most relied upon due to their ability to provide global, continuous, accurate, and easy-to-access positioning information (Orolia, 2022).

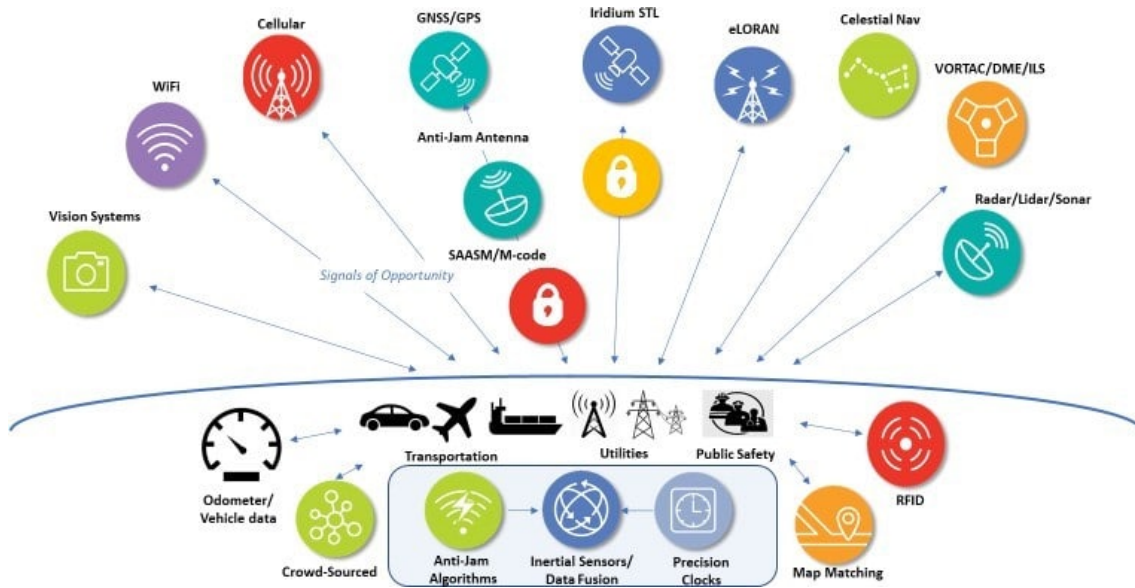


FIGURE 1.1: PNT architecture example. Source: Orolia, 2022

The Global Positioning System was the first of its kind. It was developed by the United States Defense Department and has been fully operational since 1996. Like other radio positioning systems, GPS is characterized by radiofrequency transmissions, which are further characterized by the carrier wave, its power, and the type of signal. At the same time, it is also characterized by the interaction of the satellites with the system (Batista, 2019).

In general terms, for GPS to work, the following structural requirements should be met: a control segment, land-based stations to control the system and a space segment, meaning a set of satellites equipped with atomic clocks, and a user segment, which includes the receptors or equipment of the end user (Batista, 2019).

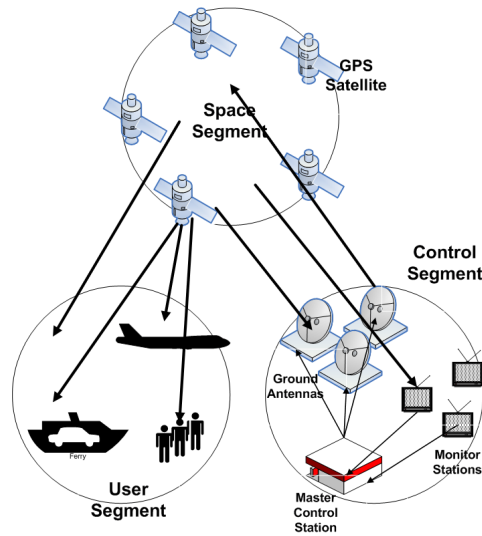


FIGURE 1.2: GPS segments. Source: Montillet, 2008, p.28.

The space segment is made up of 24 satellites that are positioned in their orbits so that the user always has at least four satellites in sight anywhere in the world, which is why GPS is a Global Navigation Satellite System (GNSS). Each satellite transmits in two frequencies, one related to navigation data and the other system information, mostly about errors and corrections (Batista, 2019).

Even though the American-developed GPS was the first of its kind and is still the system that amasses a more widespread use, other countries have followed in developing their GNSS, with the same working principles but different satellite constellations and system infrastructure (GPS.gov, 2021b).

Currently, there are several GNSS alternatives to GPS, namely three which can also provide global coverage: China’s BeiDou Navigation Satellite System (BDS); European Union’s Galileo, and Russia’s GLONASS (GPS.gov, 2021b).

1.2 Electronic Warfare and NAVWAR

The rapid advancements in information and communication technologies (ICT) have led to the development and expansion of cyberspace and many advances in electronic warfare (EW) systems (Choi et al., 2020).

EW refers to military actions performed by controlling the electromagnetic spectrum and consists of an electronic attack (EA) to control the enemy’s electromagnetic spectrum; electronic protection (EP), as a defense against EAs; and

electronic warfare support (ES), to support tasks such as surveillance and reconnaissance (Choi et al., 2020).

Owing to the convergence of ICT technology and defense science and technology, EW is widely conducted in modern military activities (Choi et al., 2020).



FIGURE 1.3: EW and its subdivisions

The most representative EA method is jamming and can be defined as an electronic or mechanical interference that interferes with RADAR, radio communications, satellite navigation or other systems (Choi et al., 2020).

In the context of GPS interferences, it refers to intentionally directing electromagnetic waves into a navigational receiver system to prevent or disrupt signal reception. Jamming intends to disrupt GNSS services by broadcasting its interference signal in the frequency band utilized in navigation by the satellites (Choi et al., 2020)

Spoofing, on the other hand, another EW method and a different type of GPS signal interference, refers to a deliberate and intentional transmission of false GNSS signals to fool a GNSS receiver, retrieving a wrong Position, Velocity, and Time (PVT) data (Medina et al., 2019).

Unlike jamming, the main intention behind a spoofing attack is to secretly force a GNSS receiver to track down the fake GNSS signals, with the main objective of providing a wrong navigational solution (Medina et al., 2019). Several studies

demonstrate the vulnerability of GNSS receptors in the face of these events, as will be explored in the next subchapter.

Proof that the military takes the threat of GNSS intentional interference such as jamming and spoofing seriously resides in the fact that it has extensively developed a concept very much associated with it: Navigation Warfare (NAVWAR).

NATO defines NAVWAR as "actions and technical measures to ensure the superiority of positioning, navigation, and timing" (Nato Standardization Agency, 2018, p.1.), meaning that NAVWAR is the concept in charge of protecting the normal use of self-navigation systems while depriving the enemy of the normal utilization of their own.

Similarly to electronic warfare, there is offensive, defensive, and support NAVWAR. Defensive NAVWAR looks to ensure the own use of PNT, such as the acquisition of an atomic clock to provide a time signal. Offensive NAVWAR aims to deprive the enemy of using their own PNT capabilities, such as interfering with their GNSS signal (Fernandez, 2020).

At last, the support measures are responsible for enriching both offensive and defensive measures by providing knowledge concerning NAVWAR, for instance, through the intelligence services providing information about the enemy's PNT sensors (Fernandez, 2020).

The development of the concept of NAVWAR also highlights the growing importance and use of PNT information in many systems, including aboard military ships and not just in navigation. GPS signal is further used in many other critical systems on board, such as weapon and combat systems.

The following figure shows an example of GPS signal distribution, with GPS information also being supplied, for instance, to the Combat System, Weapons, and Sensors, and used for time reference across systems.

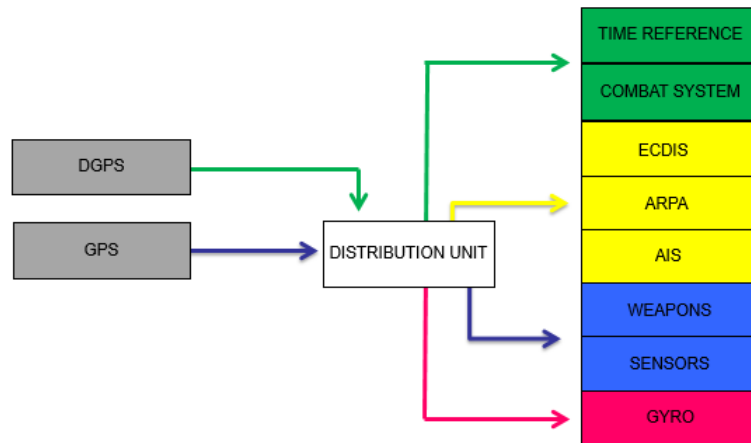


FIGURE 1.4: Example of ship GPS signal distribution

1.3 GNSS disruptions and Maritime Safety

Despite all the advantages of GNSS, several risks should be taken into account. Being a Satellite Radio Positioning System, the biggest advantage of the system is in the way that it can provide its accuracy, speed, and global reach. Still, it can also turn out to be one of its main disadvantages and its biggest vulnerability.

The GNSS, when used for positioning, navigation and timing, can have serious flaws, explained by the distance from the actual satellites to the receivers and the system's working principle. The signal's power is very low, and though it can travel long distances, it is also extremely vulnerable to interference, ionospheric effects, jamming, and spoofing. As for the latter two, Jamming and Spoofing cannot be declared as rare events as it is becoming easier to acquire jamming and spoofing equipment online (Aresta, 2017).

This constitutes a significant problem as the global-scale reliance on GNSS-based technology grows. It has been found that a full 30-day outage could potentially have a 30 billion dollar impact on the US economy, which could amount to 45 billion, depending on the season (RTI International, 2019).

This averages out to about 1 billion in a daily loss of use. In the maritime industry, these losses would range from 5.1 to 14.7 billion, with a point estimate of 10.4 billion. The large impacts are associated with port operations' interruptions and supply chain disruptions' resulting economic impact (RTI International, 2019).

Similar findings were obtained for the economic impact of a loss of GNSS in the UK. It has been estimated at £5.2bn over five days, with the majority of the

1.3. GNSS disruptions and Maritime Safety

losses being in road, maritime, and emergency and justice services, with 67 percent of all impacts (GPS.gov, 2021a).

For maritime shipping, for example, the loss of GNSS would severely disrupt all ports and the loading and unloading of containers for the duration of the outage (GPS.gov, 2021a).

And as previously mentioned, GPS outage or errors in the maritime industry is not merely a theoretical hypothesis. Spoofing profiles in Black Sea waters have become commonplace, with several incidents occurring between January 2016 and November 2018, with ships' GPSs indicating them to be moored in different Russian airports. In 2017, the 37000-tonne tanker *Atria* suffered a suspected spoofing attack while docking in the port of Novorossiysk (Burgess, 2017).

The position of the ship being displayed in the GPS-dependent systems was some 30 miles away at Gelendzhik airport, and with the captain admitting that even though GPS disruptions are not uncommon, such discrepancies have only recently begun to happen (Burgess, 2017).

Another incident related to GPS interference happened in September 2019, with a different tanker carrying 5000 metric tons of ethanol experiencing a total outage of GPS signal while approaching the shoreline of Cyprus. These incidents are reportedly on the rise, with specially targeted areas being the Black and Mediterranean Seas, the Persian Gulf, and multiple Chinese ports (Gard, 2020).

The pilot responsible for handling the situation also recognized that while GPS outages could happen for a few seconds some years ago, it was becoming increasingly common for them to last for hours or entire days at times (Dunn, 2020).



FIGURE 1.5: GPS interference reported in 2020. Source: Gard, 2020.

In addition to the intentional interference through jamming or spoofing techniques, several unintentional GPS sources of errors are inherent to the system itself. There can be errors in the ephemeris data transmission (ex: in the transmission of the satellite's location) caused by the difference between the expected and actual position of the satellite (Aresta, 2017).

In fact, in 2014, incorrect ephemeris data was uploaded to the Russian GLONASS satellites, causing positioning, navigation, and timing information issues for about half a day. Errors in the satellite clocks can also occur because, even though the atomic clocks are accurate, there is not a perfect synchronization between the timing of the satellite broadcast signals and the GPS time system (Aresta, 2017).

Even more common are errors in the receiver clock, as the quartz crystal clocks are less stable than the atomic clocks used in NAVSTAR satellites. Another common situation is the multipath errors caused by reflected signals on the antennas. As signals don't always travel straight to the antenna, they can be reflected by obstacles, which makes antennas receive direct and reflected signals (GPS World, 2016).

Atmospheric effects are also very important to consider once "space weather disturbs the ionosphere to an extent where the model no longer works and large pseudo-range errors, which can affect position and timing, are generated" (GPS World, 2016). These error sources can make GNSS systems vulnerable and, at times, unreliable (Aresta, 2017).

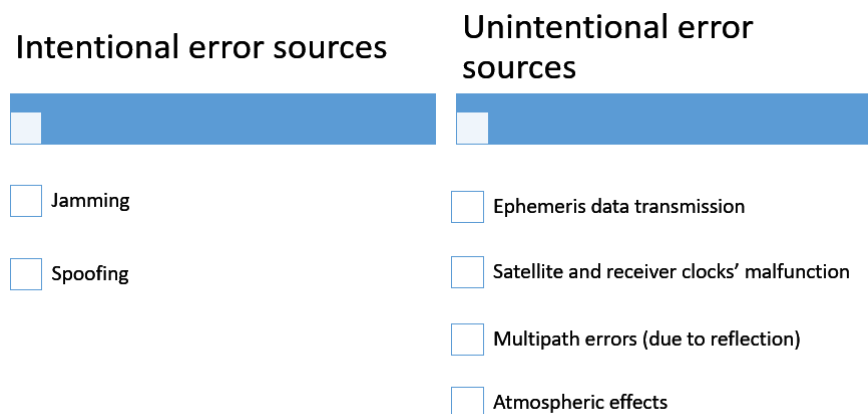


FIGURE 1.6: Intentional and unintentional GNSS errors

System resilience is the ability of organizational, hardware, and software systems to mitigate the severity and likelihood of failures or losses, adapt to changing conditions and respond appropriately after the fact (Jackson, 2007). Therefore,

assuring the robustness and resilience of these systems has become critical to many industries and sectors.

Surely one of the biggest stakeholders in attaining resilient PNT is the defense industry and its end users. There are many sources of PNT with their strengths and weaknesses. Therefore, the best strategy is to use multiple, diverse PNT sources with different failure modes and characteristics so that the strengths of another counteract the vulnerabilities of one source. Algorithms exist that can intelligently select and combine various PNT sources into a composite solution (Orolia, 2022).

The vulnerabilities of radio positioning systems can also be overrun by using a combination of technologies. These can include the use of special antennas capable of rejecting signals in certain sectors, the use of filters, or the use of augmentation systems, either ground-based (GBAS) or space-based (SBAS) (Aresta, 2017).

SBAS supports wide-area or regional augmentation – even continental scale - through the use of geostationary (GEO) satellites, which broadcast the augmentation information. At the same time, GBAS has local coverage with the help of ground infrastructures that collect errors for all the primary GNSS satellites in view and computes and broadcasts differential corrections via a Very High Frequency (VHF) Data Broadcast (European Space Agency, 2018).

The most widely used augmentation system in the maritime domain is Differential GPS (DGPS), a solution already well implemented in Portugal. The concept of DGPS is quite simple: it resorts to placing a GPS receiver in a place with perfectly well-known exact coordinates to generate corrections to the satellite's signals (Aresta, 2017). The corrections calculated at the DGPS station are then communicated via radio waves to users in relative proximity to the station using a similar data format to the satellite's GPS signal, so they can improve the precision of their positioning solutions (Direção de Faróis, 2022).

The Portuguese DGPS network currently consists of 4 DGPS stations, two being in Continental Portugal, one in Madeira, and one in the Azores autonomous regions (Direção de Faróis, 2022). Yet, despite its wide use, several countries, such as Canada, the United States, and the United Kingdom, are discontinuing their DGPS services.

This happens as these countries allege that un-augmented or space-based augmented GPS is enough to meet their operational requirements (Federal Register, 2018). The European Geostationary Navigation Overlay Service (EGNOS)

is Europe’s regional satellite-based augmentation system providing coverage for all European countries and is predicted to be progressively expanded to neighboring countries (EU Space Programme, 2021).

These augmentation technologies go a long way toward mitigating the GNSS’s system errors and provide an extraordinarily high precision (1 to 3 meters). Yet, it doesn’t tackle the issue of intentional errors, which are prone to happen in NAVWAR environments, such as jamming and spoofing. These can be tackled by other technologies which attempt to assure the signal’s integrity.

Every receiver nowadays has an automatic gain control (AGC) involved before the signal is converted and interpreted. It compares a reference value with the estimated signal power, allowing detection of the presence of interference. The gain is adjusted to make the most efficient use of the signal (Ioannides et al., 2016).

When it comes to effectively blocking and mitigating the interference, the pulse blanking technique prevails as the most popular one, blanking the signal samples once they exceed, for example, in amplitude, a certain threshold (Ioannides et al., 2016). GNSS receivers can also be equipped with multiantenna elements and adaptive processing techniques that adapt the gain to the signal and noise environment (Ioannides et al., 2016).

Algorithmic approaches are also available, with RAIM (Receiver autonomous integrity monitoring), being one of the most readily available, detects inconsistent pseudoranges (Ioannides et al., 2016).

Authentication capabilities can also be embedded in GNSS signal designs which can incorporate cryptographic techniques to provide unpredictability in data and code sequences, making it hard for an adversary to generate the same signal (Ioannides et al., 2016).

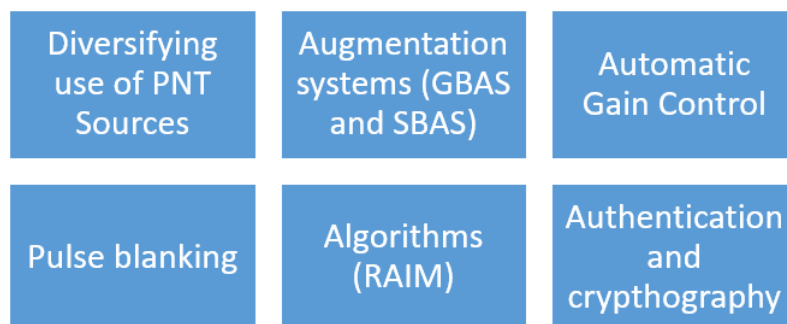


FIGURE 1.7: GNSS errors mitigation technologies and strategies

These technological solutions have gone a long way into assuring higher reliability of GNSS and effectively mitigating some of its fragilities. Yet, though they have an important role in counteracting most of the system’s unintentional errors and interferences, intentional interference situations such as jamming and spoofing remain a bigger threat. There are fewer fool-proof technological solutions, raising concern for all military operators, including the navy, due to a higher probability of facing such scenarios.

Non-technological alternatives must also be explored to mitigate the impact of GPS disruptions in maritime operations. Critical errors have been associated with procedural or human factors (V. Conceição et al., 2020), with some authors indicating the prevalence of human and organizational errors over technological ones (Hollnagel and Woods, 2005), as shown in the following figure.

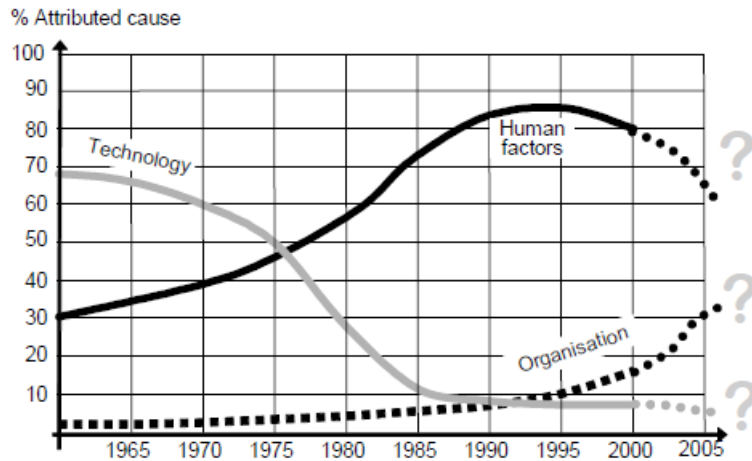


FIGURE 1.8: Changes to attributed causes of accidents. Source: Hollnagel and Woods, 2005, p.8

Associated with the overconfidence, disruptions in satellite radio positioning systems, in addition to directly impacting the equipments that rely on GPS signal, also impacts the teams that use them and rely on them for navigation safety and the task at hand. Several studies corroborate this view, correlating maritime accidents with equipment failure and associating them with human and team factors (Nepomuceno, 2020).

This is because the navigation challenge is not merely technological and technical (highly dependent on the knowledge and know-how of those involved) but also has a strong human component related to how the team is organized, communicates, and interacts. That is the challenge of Bride Resource Management: "the effective management and utilization of all resources, human and technical,

available to the bridge team, to ensure the safe completion of the vessel's voyage" (David Patraiko, 2014, p.2).

The importance of BRM is demonstrated not only by the fact that its certification is mandatory in the merchant navy but also by recent studies that point towards the need to approach the training of military vessels based on BRM (Cavaleiro, 2020). It is a concept focused on the utilization of the available resources (people, equipment, information, etc.) and on the improvement of coordination and performance (Tvedt et al., 2018).

It intends to modify the attitudes of individuals towards safety, highlighting the importance of non-technical skills (NTS). NTS are "the cognitive, social and personal resources skills that complement technical skills and contribute to safe and efficient task performance" (Flin and O'Connor, 2017 p.1). NTS examples are communication, briefing, team leadership, decision-making, adaptability, Situational Awareness, interpersonal relationships, and team coordination (Powell and Hill, 2006).

Besides failure to correct known problems and planning, Conceição and coworkers (2019) found decision and perception errors and problems associated with inter-ship communication and BRM. The importance of BRM and human factors are exacerbated by the changes in the navigation working domain, with the introduction of new information technology that enhances the complexity of the bridge system and team working.

Yet, despite this and the impact of the adversity of GNSS-denial in maritime operations, in the case of the Portuguese navy, previous studies showed that there is no doctrine and no training routine regarding GPS signal denial situations. The exceptions are the ships that take part in the Operational Sea Training (OST) or national and international exercises (Trindade, 2018). Internal procedures aboard ships to face GPS outage or disruption were also nonexistent (Aresta, 2017).

1.4 Joint Cognitive Systems

"Building resilience by design requires a holistic approach and understanding of interdependencies between people, processes and technology" (NATO, 2022, p.4).

A cognitive system is, put simply, a system that learns and develops knowledge based on experience to pursue some order. Joint Cognitive Systems' theory is precisely a way of attaining such a holistic approach and understanding. The joint

cognitive systems (JCS) is a field of cognitive systems engineering (CSE), which comprises the systems in which humans interact with machines to maintain control of a safety-critical activity (Hollnagel and Woods, 2005).

As Hollnagel and Woods (2005) showed in their book, the difference between a cognitive system and JCS becomes easily understandable if we look at the level of an individual: a human being is a cognitive system, but not a JCS; a human using an artifact (a technological one, for example) is a JCS; a group of people, even as small as two such as the pilot and co-pilot in the cockpit, is a JCS. The ship's bridge is also a JCS, entailing all team members and technology, contributing to attaining the objective of safe navigation while complying with the pre-defined route.

To better understand JCS, it is important to know the following threads on which CSE focuses. The first is how people cope with the complexity resulting from the many technological and sociotechnical developments. The second is how people use artifacts in their work and how humans and artifacts can be described as joint cognitive systems. Finally, this extends the scope from the focus on the interaction between humans and machines to how humans and technology can effectively work together (Hollnagel and Woods, 2005).

These threads give rise to the human-machine coagency concept, which studies how humans and artifacts operate and, more importantly, how they can best work together to avoid the dangers of uncontrolled complexity.

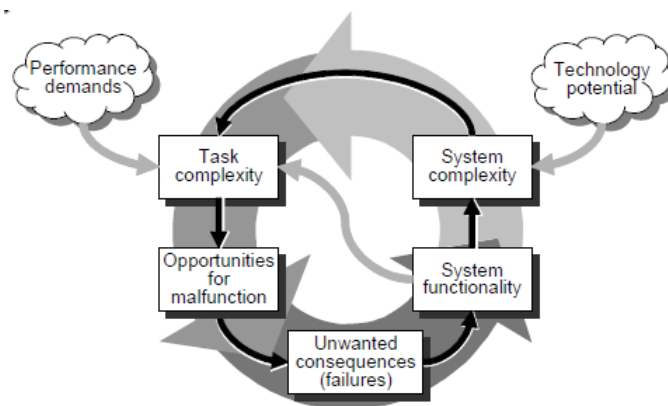


FIGURE 1.9: Self-reinforcing complexity cycle. Source: Hollnagel and Woods, 2005, p.4

The classical human-machine model represents interaction exclusively as the exchange or transmission of input and output. CSE brings a paradigm change by representing human-machine systems as this coagency, where users are parts of a

whole, and the environments are dynamically coupled. The actions and events are mutually dependent (Hollnagel and Woods, 2005).

Artifacts are not just passively used but do also have a determining effect on human performance. The CSE perspective goes beyond describing how humans interact with artifacts and instead consider how the human-artifact ensemble performs as a single unit (Hollnagel and Woods, 2005).

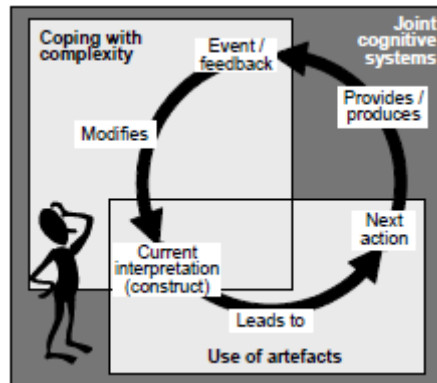


FIGURE 1.10: Merging the threads of CSE. Source: Hollnagel and Woods, 2005, p.69

In other words, what should be studied is neither the internal functions of either human or machine nor the interaction between them, but rather the external functions of the JCS as based on human-machine coagency. This change is consistent with the principle that humans and machines are equal partners and should be described on equal terms (Hollnagel and Woods, 2005).

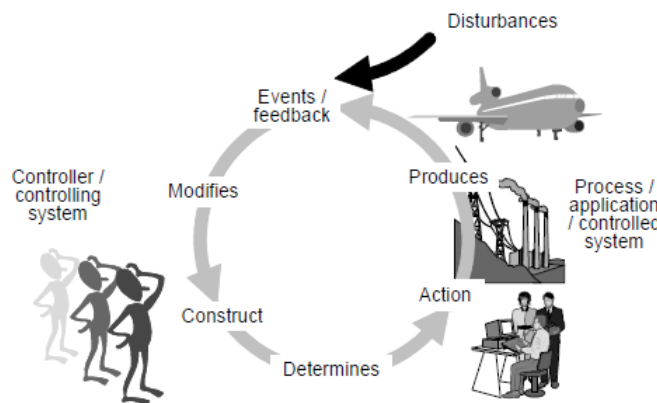


FIGURE 1.11: Basic cyclical model. Source: Hollnagel and Woods, 2005, p.20

The CSE has three basic methodological principles. The first principle is based on carefully identifying situations where problems may arise, emphasizing the reality of the issues. As previously mentioned, Trindade (2018) and Aresta (2017) have identified gaps in how a GNSS disruption is handled. The second principle is to describe the conditions associated with the problems, either as potential causes or as factors that affect how an event develops. The third and final principle is to propose or construct the means by which such situations can be mitigated or prevented, which is the end goal of the present study (Hollnagel and Woods, 2005).

Based on the second methodological principle of CSE, the literature now points to safety and performance in human-machine systems emerging from several variables. The assessment of precursors to safety and performance is thus an essential part of predicting and improving outcomes in human-machine systems.

Stowers and coworkers (2017) developed a framework that details several inputs and processes that collectively influence safety and performance. The inputs are divided according to human, machine, and environmental information. And the processes are divided into attitudes, behaviors, and cognitive variables. Each class of inputs influences the processes and, subsequently, the outcomes that emerge in human-machine systems (Stowers et al., 2017).

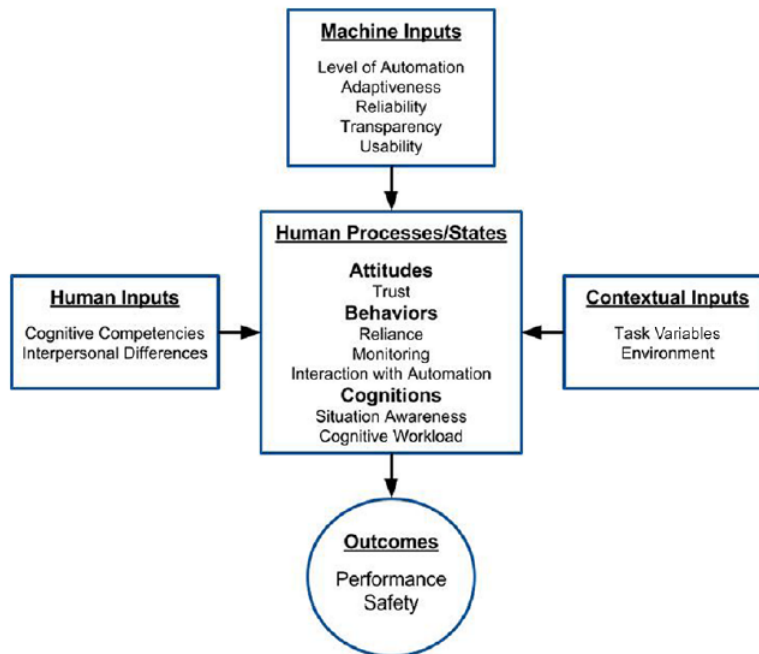


FIGURE 1.12: Measurements for human-machine systems. Source: Stowers et al., 2017, p.3

This framework identifies and presents several constructs within Human Processes/States as they relate to two key outcomes of interest: safety and performance. More specifically: Attitudes, Behaviors, and Cognitions.

Yet, the division between human processes/states and human inputs, as well as the clear categorization of attitudes, behaviors, and cognitions, is not fully supported by literature (Grech et al., 2008).

It is more common to find in reference manuals and publications the general use of the term human factors, serving as the umbrella term for all the mentioned measurements (Ross, 2017): Competencies, Demographics, Experience, and Interpersonal differences, Trust (in this case in automation), Interaction (in this case with both technology and team members), Situational awareness and Workload (WL). These measurements are themselves fully supported by literature, as the following paragraphs will seek to demonstrate.

Trust in automation has been identified as a key contributor to acceptance in many machines, becoming increasingly important as new devices are introduced (Körber, 2018). Under-reliance on automated machines can have a negative effect. For example, frequent false alarms in various machines can cause users to ignore critical indicators, causing accidents (Parasuraman and Riley, 1997).

On the other hand, too much reliance can lead humans not to use automated machines as intended (Dzindolet et al., 1999) because of the emergence of the complacency feeling, which is defined as the wrongful assumption that the device is functioning correctly, resulting in a lack of vigilance (Parasuraman and Manzey, 2010).

Human-machine systems performance is also related to Situational Awareness, as lower levels can contribute to the same complacency effects (Endsley and Robertson, 1996). Situational Awareness can be defined as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (Endsley and Kiris, 1995, p.2).

Decrements in monitoring and SA elevate the risk that operators will fail to detect and manage machine failures that arise in a timely manner, thus increasing the potential for negative safety outcomes (Bahner et al., 2008).

It has been identified that SA and WL are variables that emerge as clear cognitive indicators of performance and safety across many types of human-machine

systems (Stowers et al., 2017). WL is the user's perceived level of mental effort that is influenced by many factors, particularly task load and task design, which are measured, and can help assure safe, successful, and efficient system operations by the crew (Marques et al., 2015).

WL has been correlated negatively with task performance, with a greater cognitive load also resulting in longer task completion times (Biondi et al., 2021). All the while, a study conducted in the Portuguese navy identified SA and WL as one of the main non-technical skills to operate in a maritime context and suggests further training of these competencies through simulation-based training (SBT) (Cavaleiro, 2020).

There is also growing evidence suggesting that individual differences, such as age or sex, can also play a role in Trust and complacency (Muir and Moray, 1996). For older adults, it has been hypothesized that deficits exacerbate this problem in attention (Vincenzi and Mouloua, 1999), and thus they should exhibit greater complacency effects.

As for the relationship between age and team dynamics, it has been hypothesized that older team members and older teams, in general, tend to make fewer decisions and interact less. They also tend to be less responsive, less willing to receive and cope with new information and reduce information search (Streufert et al., 1990).

Expertise and skill, which are instinctively related to performance, have also been found to lead to higher detection of automation failures, which is important for the safety and performance of human-machine systems (Stowers et al., 2017).

This reinforces the importance of quantifying skills, expertise, and experience to ensure that the operator is prepared and equipped to interact with the machine (Parasuraman and Manzey, 2010). The same happens with training, hardly surprisingly being related to higher performance and safety levels across fields, industries, and job and task levels (Aragon et al., 2014).

1.5 Resilience engineering

"Resilience is a property intimately associated with the organizations' capacity to avoid, contain and mitigate accidents" (Antunes and Mourão, 2011, p.3). A resilient system can deal with unexpected events or failures and catastrophes.

Having a resilient system does not mean that it absolutely cannot fail, but, that it somehow has a way to be back online by itself when submitted to a vulnerable situation. This leads to the fact that a resilient system must instate both technology and its operators and be robust and flexible (Aresta, 2017).

Resilient design implies integrating qualitative and quantifiable resilience requirements into systems and structures (NATO, 2022). Yet, it is also often argued that system resilience can only be observed when a system is exposed to unfavorable events, perturbations, or signals and inputs beyond normal operating or design conditions. Thus, a longitudinal study of the system and events over time provides the best opportunity to observe, measure, and comment on the resilience performance of the system design (Punzo et al., 2020).

Therefore, the framework developed by Punzo and coworkers (2020) for a continuous, cyclic resilience presents the building up of a system as a continuous learning process based on the analysis of the system, its weaknesses, and occurred failures to instate measures to prevent these from happening again, starting the cycle all over again. This framework can be called the resilience wheel (Punzo et al., 2020).

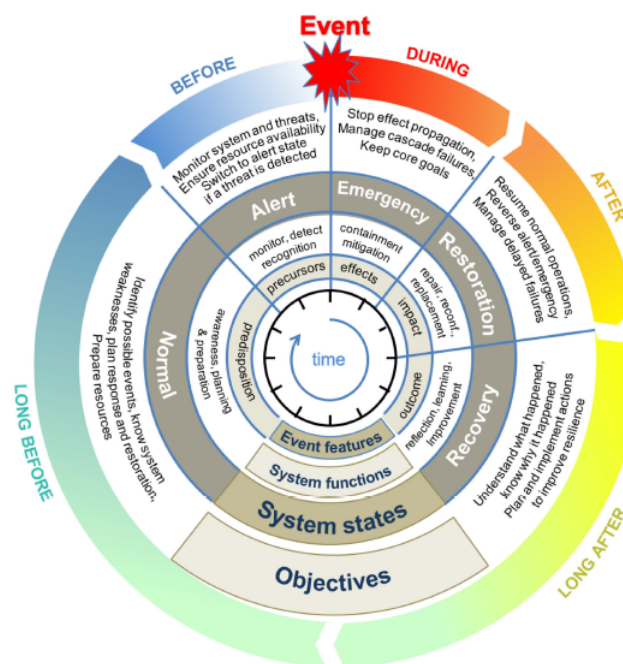


FIGURE 1.13: The resilience wheel. Source: Punzo et al., 2020, p.7

Safety is one of the most crucial parts of the performance in maritime operations and most activities, often the main one. This is especially the case in navigation, with the demand for resilience being linked with the need for safety.

The previously mentioned resilience wheel's long after and long before phases, which are related to understanding and learning as well as improving and preventing, have been traditionally linked to a Safety-I perspective. Safety-I looks for "the absence of unwanted outcomes such as incidents or accidents" (Hollnagel, Wears, et al., 2015, p.8), with the goal of ensuring that the number of events that can go wrong and cause harm is as low as possible (Hollnagel, Wears, et al., 2015). Yet, as illustrated by Hollnagel (2015), it is easy to see how this Safety-I perspective can be extremely limiting in most activities.

This is evident just by looking at the number of times things go wrong and times things go right. There are far more case studies for when things go right (Hollnagel, Wears, et al., 2015).



FIGURE 1.14: The imbalance between things that go right and things that go wrong. Source: Hollnagel, Wears, et al., 2015, p.9

Resilience engineering acknowledges that acceptable outcomes and adverse outcomes have a common basis, namely everyday performance adjustments, and because many different work situations today are complex and hard to deal with, it is impossible to prescribe what should be done in any detail except for the most trivial situations, and the reason why people nevertheless can work effectively is that they continually adjust their work to current condition (Hollnagel, Wears, et al., 2015).

So these performance adjustments should be looked at in their entirety. This means analyzing not just the adverse but also the acceptable outcomes; this is where the concept of Safety-II emerges. To make sure things go right, we cannot just prevent them from going wrong but also understand how they go right (Hollnagel, Wears, et al., 2015).

Yet, the way towards more resilient systems, even Joint Cognitive Systems, is not to choose one type of safety over the other. Safety-I and Safety-II represent two complementary views of safety rather than two incompatible or conflicting approaches (Hollnagel, Wears, et al., 2015), and so they can and should be looked at together.

1.6 Varieties and representations of work

Design, management, and work analysis tacitly assume that we know how things are done or should be done. Since humans and organizations are supposed to follow procedures, rules, and guidelines, the planning and management of work, including accident investigation and risk assessment, assume that compliance is the norm. Yet, work is never completely regular or orderly, except in exceptional cases (FRAM, 2022).

Therefore, it results in a difference between Work-As-Prescribed (WAP) and Work-as-Done (WAD). WAP is a formalization that takes on several forms in organizations, including laws, regulations, rules, procedures, checklists, standards, job descriptions, management systems, and so on (Shorrock, 2017).

On the other hand, WAD is actual activity, what people do. It is characterized by activity patterns to achieve a particular purpose in a specific context. It takes place in an environment that is often not as imagined, with multiple, shifting goals, variable and often unpredictable demands, and sometimes degraded resources (Shorrock, 2017).

It is, therefore, inadvisable to assume that work is as we imagine and that compliance guarantees success. Work-as-done (WAD) will always be different from other varieties because it is impossible to know in advance what the actual conditions of work will be, not least what the demands and the resources will be (FRAM, 2022).

The functional resonance analysis method (FRAM) is a method to analyze how work activities take place. This is done by analyzing work activities to produce a model or representation of work. Each activity or function has six possible couplings to other activities: Output (O), Input (I), Control (C), Time (T), Precondition (P), and Resource (R) (FRAM, 2022).

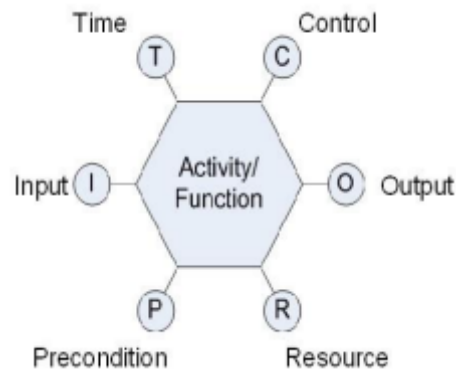


FIGURE 1.15: The six couplings of a FRAM activity/function.
Source: FRAM, 2022

This model can then be used for specific types of analysis, whether to determine how something went wrong, to look for possible bottlenecks or hazards, or to check the feasibility of proposed solutions or interventions, for example (FRAM, 2022). The following image provides a part of the FRAM model that will be developed in chapter 3, with the function "Perform port study" and its preconditions.

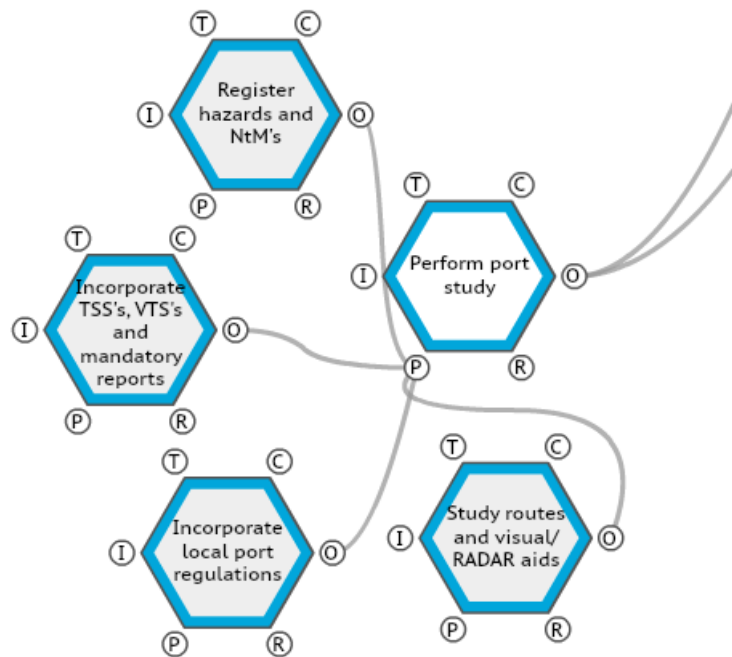


FIGURE 1.16: FRAM map exaple: Function "Perform port study" and its preconditions

1.7 Navigation doctrine in the Portuguese navy

Maritime navigation can be defined as "the control of the ship's direction associated with the planning and execution of navigation"¹ (Estado-Maior da Armada, 2008, p.23).

Navigation, in the Portuguese navy, can be divided into three main types: Coastal navigation, which can be done closing in or along the shoreline, generally within 3 miles off the shore or the closest danger; Ocean navigation which can be done at great distances off the coast or the nearest hazard; and restricted waters navigation or piloting which is done in ports, rivers, canals or any other situation where the maneuver of the ship is limited, be it because of depth availability, traffic density or the characteristics of the local currents and tides (Estado-Maior da Armada, 2008).

These different types are associated with different requirements for accuracy, navigation methods, and procedures. The study focuses on navigation in a piloting situation with good visibility. (Estado-Maior da Armada, 2008)

This type of navigation demands excellent accuracy and steadfastness in the control of the ship's position. The primary navigation method in piloting with good visibility is visual fixes, meaning navigating by determining the course from other places on the earth's surface, usually conspicuous marks along the coast (Estado-Maior da Armada, 2008).

However, satellite navigation can also be used as a primary method in operations demanding higher position accuracy, such as hydrographic surveys or mine warfare (Estado-Maior da Armada, 2008). Under normal circumstances, the operational standard for position accuracy in this type of navigation is 10 m, which is also the standard set by IMO regarding Harbor Entrance and Approaches (IMO, 2001).

As it is prescribed that the GNSS shouldn't be the primary method, it is expected that the GNSS disruption doesn't have an impact on task accomplishment in the present study. On the other hand, performance and compliance with procedures and requisites may be affected as a previous study identified over-reliance on GNSS information even while the system alarms were on, with operators failing to report on the weak signal quality (Trindade, 2018).

¹Translated by the author from the original text: "Entende-se por condução da navegação o exercício de direcção do navio associado ao planeamento e execução da navegação"

The continuous high proximity to hazards of piloting also means that planning should be especially thorough and executed by a purpose-trained team, the piloting team, to assure a faster, safer, and more effective navigation (Estado-Maior da Armada, 2008).

1.8 Piloting teams

The piloting team is the bridge team responsible for piloting, which is executed in situations where the ship’s maneuver is limited. Therefore, the organization of personnel on the ship’s bridge is tailored specifically to that circumstance to respond to the higher demand for safety, precision, and tempo (Estado-Maior da Armada, 2008). The tasks, supporting artifacts, and systems associated with piloting are displayed in the following figure.

Task	Artefacts	Systems ^{a)}
1. Team leader	Schemas	gyro, speed log, rudder angle
2. Teamwork coordination	Schemas	Headset comms, procedures
3. Define, adjust priorities, goals	Schemas	
4. Avoid navigation hazards or vessels		Helm, telegraph
5. Ship’s safety		
6. Communication with other vessels and shore stations		VHF comm, visual and sound signals, AIS ^{c)} text message
7. Determine current, future and desired position	Speed/Time/Dist.Calculator, Hand notes, schemas, nautical chart	Gyro, radar, ECDIS, GNSS, INS ^{b)} , speed log, AtoN ^{d)}
8. Determine corrections to course, orientation, and speed to attain the desired position		
9. Determine available safe space/time to manoeuvre		
10. Detect, Identify, classify and track navigational dangers, other than vessels	Binocular	Gyro, radar, AIS, AtoN
11. Detect, Identify, classify and track other vessels		
12. Take some measurements	Schemas	Gyro, echo sounder. Speed log, rudder angle, ECDIS

FIGURE 1.17: Tasks, supporting artifacts and systems associated with piloting. Source: Conceição et al. (2020), p.439

If the visibility is considered good, the Navigation Officer leads the piloting team (Tasks 1 to 4 and 7 to 12). He has the conn and the responsibility of assuring safety and the control of positioning and time. Besides the Navigation Officer (NAVO), the team is constituted of the following members (Estado-Maior da Armada, 2008):

- Officer of the Deck (Tasks 2, 5, and 6) a watch officer responsible for aiding the NAVO with the visual navigation control, assuring bridge routine, ceremonial procedures, and internal safety, and overseeing the RADAR operator;

- Bearing takers (Tasks 10, 11, and 12), responsible for identifying the conspicuous visual marks and reporting their azimuth while also acting as lookouts, reporting collision avoidance visual information;

- Echo sounder operator (Task 12), responsible for operating the sounder and reporting its values according to the procedure;

- Radar operator (Tasks 7 to 12), responsible for operating the RADAR, controlling and reporting collision avoidance information, providing positioning information, and assessing the NAVO;

- Electronic Chart Display and Information System (ECDIS) operator (Tasks 7 to 12), responsible for registering positioning information on the system and assessing the NAVO;

- Chart plotter (Tasks 2, 7 to 10, and 12), responsible for providing information about which conspicuous marks to use by the lookouts, plotting the positioning information on the chart, and assessing the NAVO.

The constitution of the piloting team may vary slightly depending on the class and specificities of the ship (Estado-Maior da Armada, 2008).

For the success of piloting, it is necessary to ensure information flow through the report cycle, which constitutes the core of bridge communication and procedures in pilotage. The objective of the report cycle is to provide information that allows the NAVO to provide answers to the following questions with the help of the other three main positioning information sources (chart, RADAR, and ECDIS) (Estado-Maior da Armada, 2008):

1. Is the ship on the pre-defined route (in case of non-compliance, what is the distance to the planned trajectory, suggested course, and arrival time);

2. What distance and time are left to the next wheel over point?

3. What is the distance to the closest hazard? Should the route be adjusted? If so, when and how can the ship get back on course after the adjustment?

4. Is the ship on schedule? If not, should there be a speed change? Does the estimated time of arrival (ETA) have to be adjusted?

5. What is the impact of the external factors (currents, visibility, vessel traffic, waves, and wind)

6. What is the minimum depth expected on the current route?

The NAVO's report is the first of the report cycle, answering all the previous six questions. It is followed by the report of the other intervening parts, providing information regarding the first three questions in the following sequence: RADAR, chart and ECDIS (Estado-Maior da Armada, 2008).

Though it may vary, each iteration of the report cycle should occur every three minutes, except when approaching a wheel-over point. When doing so, the report cycle should cease and give way to a countdown in distance and time to the wheel over point, promptly resuming the report cycle after the turn is completed (Estado-Maior da Armada, 2008).

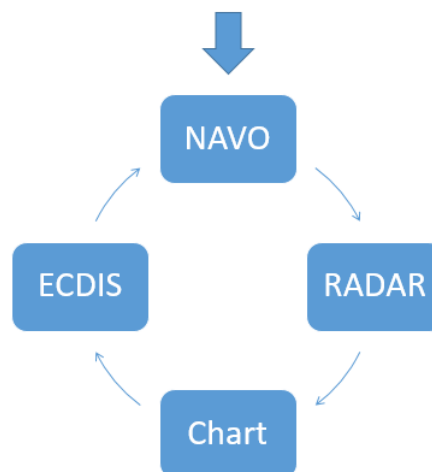


FIGURE 1.18: Order of the main intervening roles in the report cycle.

1.9 Navigation Training in the Portuguese navy

In the Portuguese navy, the entity responsible for ensuring performance assessment, evaluation, and compliance with organizational standards, as well as providing the necessary operational training, is the Portuguese Tactical Center (PTC)².

It is equipped with several simulators, including the Navigation Simulator (NAVSIM) with seven bridges; they can be used for simulation-based training (SBT), with three bridges being located in the PTC and the four remaining in the Naval Academy, all network-based.

²Centro Integrado de Treino e Avaliação Naval (CITAN) in Portuguese

According to the ship's previous training history and upcoming missions, continued training and evaluation are supported by different training programs at sea and at the shore. In the latter case, they can happen aboard or in training facilities such as the PTC. Each of these training plans involves executing a set of exercises both on board and in the respective simulator.

The standard piloting exercise (PILOTEX) performed in training is a visual piloting exercise and its purpose is to train the accuracy of the piloting teams in conducting confined waters or swept channel navigation. It involves planning a fictitious or real geographic scenario considering a transit in restricted waters. Upon completion of the exercise, each ship should compare the planned route with the track that was effectively followed (e.g., comparing the chart plotting with the GPS log) to determine the maximum distance gap.

Although the latter is listed as the only performance measurement for the exercise, there are other possible and useful measurements that provide feedback for teams and improve performance, such as individual skills, leadership, situational Awareness, communication, teamwork, and decision-making (V. d. Conceição et al., 2017).

Therefore, at the PTC, other evaluation and feedback mechanisms provide a qualitative assessment of compliance with procedures and objectives. This is the case of evaluation checklists, an extensive list of preparations, procedures, and actions that teams in each exercise must perform. The checklist aids the evaluator in the evaluation, which is formalized through a report indicating the result, a global qualitative performance indicator. It also lists positive aspects, training priorities, and Aspects to Improve (AtI), which can be categorized as minor, significant, or critical.

1.10 Summary

This first chapter starts with defining PNT, explaining its sources in further detail to Satellite Radio Positioning Systems, GPS, and other GNSS, and exploring the basic working principles. It continues with the definition of Electronic Warfare, its subdivisions, and methods, explaining in more detail jamming and spoofing. It defines Navigation Warfare and its consequences, followed by the other uses of GPS signal besides the bridge and navigation. It devotes its larger section to the GNSS disruptions that have occurred in recent years, calling to the attention that they are on the rise, especially intentional ones.

It shows and details other possible unintentional sources of errors related to the system itself, explaining the most recent technological advances that maximize the possibility of detecting and mitigating such disruptions. Yet, it continues to stress that one of the leading causes of maritime accidents is human factors. So people and technology should be taken into account while studying the impact of a GNSS disruption in piloting, mentioning previous studies in the Portuguese navy with findings that suggest improvements can be made in the response of piloting teams to these incidents.

The following section addresses the methodology that can and should be used in cases where people and technology are working together: Joint Cognitive Systems. It talks about its threads, methodological principles, and implications while mentioning other frameworks with specific measurements that should be used for these human-machine systems, going into detail about which measurements should be used and what literature suggests.

It continues with the definition of resilience and the principles of resilience engineering, highlighting that work, in reality, is never completely regular or orderly and that FRAM is a method that allows the representation of work to analyze the difference between Work as Done and Work as Prescribed.

The chapter finishes summarizing the navigation doctrine and training in the Portuguese navy when it comes to piloting and piloting teams.

The following chapter will start with the connection between the literature review and the chosen research questions, as well as the options that were made for the study's design. It will also mention the ethical options and data protection measures. It will go into detail about the measurements chosen and why finishing with some technological considerations about the NAVSIM and the study's limitations.

Chapter 2

Methodology

2.1 Research questions

Chapter 1 provides an overview of the relevant literature to the study. It starts by highlighting the problem that motivated the study of GNSS disruptions and moves into the concepts of JCS, safety, and resilience engineering, finishing with a summary of the relevant navigation doctrine and training. Looking into what went wrong and what went right, the good and the bad adaptations to the working conditions, to continuously improve resilience and performance. Performance in navigation is directly linked to safety, and a mature safety perspective involves both a Safety-I and a Safety-II analysis (Hollnagel, Wears, et al., 2015). The study intends to use these two perspectives to study resilience in NAVWAR environments.

Therefore, the methodology for the study, including the observations and experimental protocol, was developed to provide the answer to the main research question: "What are the success factors for resilient navigation in NAVWAR environments?". To do so, using the same perspective, we must first look at the differences in the result, which teams had higher performance levels, and which teams performed more resilient navigation (Sub-question 1). Then the natural question follows, the why. Why these performance differences? What explains them? This is the second sub-question, "What were the factors that determined the differences in Q1" (Sub-question 2), using all the data collected, as suggested by literature and the pilot tests. Yet, because human factors have been overwhelmingly present in maritime accidents and previous studies on GNSS failure and denial have failed to address them, the present study intends to fill this gap by focusing most of its measurements on human factors. Therefore, an entirely separate sub-question relates to them, "How do human factors determine the resilience of navigation?" (Sub-question 3).



FIGURE 2.1: Research questions

2.2 Study design and ethics

The study was based on a total of 6 observations in the Portuguese navy's navigation simulator (NAVSIM). Different piloting teams from various ships of the national fleet were chosen as subjects as they were the performers of piloting in their respective ships, with the formation and training necessary. This means that, in the case of a GPS outage or denial situation, they would be in charge of dealing with and overcoming it.

They performed a standard piloting training, PILOTEX. The main goal of this exercise is to train the piloting team in conducting restricted waters navigation with the best possible accuracy and effectiveness. This means that the team should be able to continuously monitor the ship's position in compliance with the route while monitoring and avoiding environmental hazards or possible collisions.

The chosen scenario was the port of Lisbon, as it is the port in which the subjects of the study have more experience and training, minimizing the variability that would be introduced if a port that the teams had less or no experience was chosen. This logic was applied in defining the parameters of the scenario as well. Minimizing variability is achieved by reducing the impact of a different and more difficult geographic location. It is also achieved by reducing the impact of vessel traffic, or meteorological and oceanographic conditions. In this way, it is possible to maximize the meaning of the different measurements. In turn, this will allow being more confident that they are related to the GNSS disruption and the differences between the teams.

The starting point is the position $38^{\circ}39.4'N$ $009^{\circ}19.5'W$, and the endpoint is $38^{\circ}40.4'N$ $009^{\circ}08.5'W$. The piloting teams were responsible for the planning and

the execution of the exercise, and every team’s route was made up of 5 legs, except for one team, which had a six-leg route. The standard scenario used in the study can be visualized in the following figure.

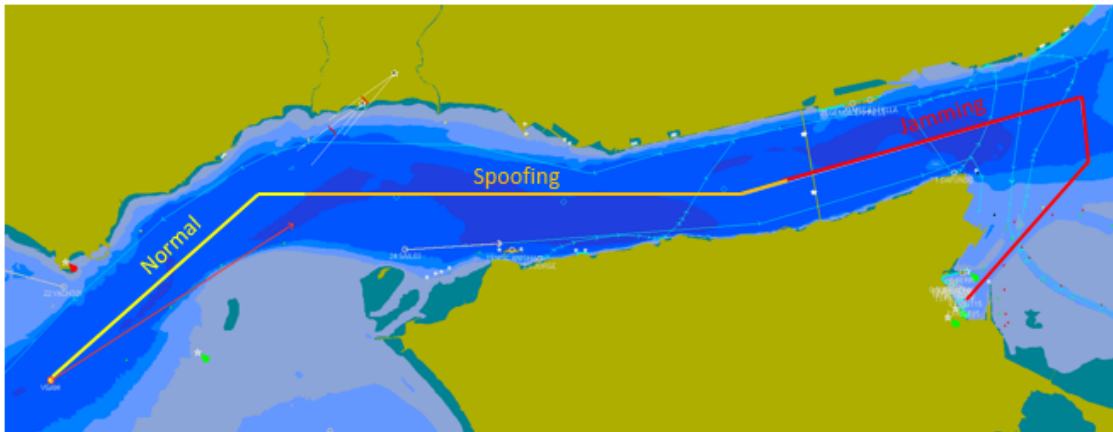


FIGURE 2.2: Standard scenario used in the study

Before the beginning of the experimental study with the piloting teams, three pilot tests were conducted with the cooperation of the Portuguese Naval Academy and three groups of midshipmen from the second, third, and fourth years, with a total of 15 participants.

Question	Team			Total/Avg
	A	B	C	
Sex	3M/2F	5M/0F	3M/2F	11M/4F
Age	21,6	20,2	22,4	21,4
Years in the navy	3,0	2,0	4,0	3,0

TABLE 2.1: Demographic data of the pilot tests participants

In the experimental study, six sessions with six different piloting teams were performed between the 1st of June and the 13th of July with piloting teams from various ships, from small patrol boats to corvettes. There were a total of 42 participants, and in all sessions, both video and audio were recorded using one audio recorder, three cameras (with three backup cameras), and two chronometers for common time reference.

	Team						Total	Stand. Dev	Max	Min
	D	E	F	G	H	I				
Sex	7M/1F	5M/0F	5M/2F	7M/0F	7M/1F	7M/0F	38M/4F			
	Average	Average	Average	Average	Average	Average	Global avg			
Age	33,9	33,0	31,0	32,0	30,4	29,6	32,1	1	34	30
Years in the navy	15,1	14,4	12,7	12,1	11,0	12,3	13,1	1	15	11
Experience aboard ships (years)	6,6	6,8	4,4	5,4	5,6	4,9	5,7	1	7	4
Hours at sea	5870,9	6700,0	971,4	3544,6	6282,9	5785,7	4673,9	1858	6700	971
Time on current ship (months)	17,4	6,2	11,0	13,7	14,0	12,4	12,5	3	17	6
Time on current team (months)	12,0	5,4	7,6	8,1	11,0	7,1	8,8	2	12	5
Months since last full training plan	42,0	78,0	20,0	24,0	2,0	2,0	33,2	24	78	2
Number of SIMPILOTEX's in 2022	11,0	6,0	2,0	2,0	6,0	14,0	5,4	4	14	2

M - Male ; F - Female

TABLE 2.2: Demographic and Professional Background data of the study participants

Each experiment with each team had three distinct moments: The first, in the first leg, characterized by normal availability of GNSS signal; the second, in the second leg, undergoing a GNSS spoofing disruption and the third, in the remaining legs, undergoing a jamming disruption. The disruptions were always introduced when the ship's heading was steady, after the wheel over point, to have minimal interference with the change of course.

In the pilot tests, the scenario was the Port of Setúbal, as it was the only port all teams of midshipmen had experience in and had support materials for. The teams performed only two legs. Therefore, although the three distinct moments were the same, both the spoofing and the jamming disruptions were introduced in the second leg.

The evaluators of the PTC were responsible for evaluating and providing feedback to the piloting teams, as they usually would as part of the ship's training plan.

The study required previous approval from the Portuguese Navy's Fleet Command, which was preceded by several coordination meetings with Fleet Command and the PTC to define the planning, ship selection criteria, and security and privacy measures.

The week before each experiment, the teams received a leaflet with general information about the study and the experiment (Annex I) and were requested to sign the informed consent form. Each experiment was preceded by a study briefing containing the information presented in the leaflet. It also included some rules and practical considerations. For example, the interaction between the participants and the PTC staff was not allowed during the experiment. Participants should also

refrain from sharing any detailed information about the study to ensure the integrity of the data collected.

All data collection and processing complied with the data protection laws and standards in force at the time of the study, namely the EU's General Rules of Data Protection and the national and NATO norms for classified information. The anonymity of all participants and naval units was assured through code names and image distortion, among other measures to disallow the possibility of identification or association with any of the participants.

2.3 Measurements

The study's data collection and measurements were adapted from the framework developed by Stowers and coworkers (2017), using only quantitative measurements to assess a human-machine system such as a piloting team effectively. The terminology was significantly changed to be in accordance with other literature on human factors, as mentioned in chapter 1.

According to the aforementioned framework, human-machine systems have three input variables: Human, Machine, and Contextual. In the present study, machine inputs remained constant as the equipments used by all participants were the same and therefore had the same level of automation, transparency, and usability. It is also the case with the contextual inputs, as the task variables and the environment didn't vary, as the bridge, equipments, scenario, and parameters remained unchanged throughout the different experiments, changing only the introduction of the jamming and spoofing, yet, this was done in the same manner for each experiment.

Only the human inputs named in the framework had real variability, as different teams with different participants took part in the study. Yet, Demographics, Experience, and Interpersonal differences were considered human factors, along with most other measurements that will be further referred. The 3 aforementioned factors were measured through the filling of a Demographics and Professional Background Questionnaire (DPBQ) (Annex II), adapted from Nepomuceno (2020).

This questionnaire was filled by each participant previous to the execution of the exercise. It contained information regarding demographics and background/-experience, as well as the ship and level of training of each team. Sex and age differences between the teams were negligible, and other information didn't seem relevant to the study as a possible success factor. Only experience and training data

ended up being analyzed, namely: Time on the current team, Months since the last full training plan, and the number of SIMPILOTEX in 2022.

Time on the current team seemed a particularly interesting data to analyze, as current navy HR management sometimes requires a relatively high personnel rotation between naval units. Even more so because the potential impact of this management option to piloting teams within the Portuguese navy hasn't been studied yet.

Pilot tests aided in developing the protocol and testing for the best sequence of events of the experiment. Not only that, but they raised the possibility that specific knowledge of the impact of GNSS disruption on the bridge equipments could be another human factor worth analyzing as it could be indicative of success in better handling the GNSS disruption.

Therefore, the "GNSS-dependent equipments/systems questionnaire" was developed and used for measuring this specific cognitive competency in the system. In this questionnaire, the participants were asked to identify, out of a list of bridge equipments and systems, which worked with GNSS information (Annex III).

As mentioned in chapter 1, attitudes measurement in human-machine systems tends to be overwhelmingly identified with measuring Trust. Therefore Trust in the bridge equipments was measured through the Trust in automation survey developed by Moritz Koerber (Körber, 2018) (Annex IV), which is meant to be filled only by those who are operating directly with technology. It has 19 items on a 5-level scale, assessing the operators' perception of the reliability, predictability, and familiarity of the equipment.

It also measures their overall propensity to trust, the developers' intention, and Trust in automation. The final score of each parameter is calculated through the average result of the different questions that assess it. Given the fact that the main question of the study is to determine the success factors for resilient navigation, the three chosen parameters to analyze were the ones most directly associated with the Trust and reliability of the information displayed on the equipments: reliability, the propensity to trust and trust in automation.

Interaction changes were measured regarding the variation in quantity and quality of interactions within the team. The same happened between each operator and their respective equipments. In terms of the interactions between team members, the number of complete and incomplete report cycles were counted, the

number of interactions outside the report cycle between each team member, and their total number.

After the pilot tests, the interaction changes with technology, namely with the ECDIS equipment, as its use is most directly related to the availability of GNSS signal, were also considered a possible success factor, and therefore a coding was developed based on the most used tools, and the following interaction categories were counted: access to the menus/parametrization; zoom/range change; confer contact information; use of navigational tools such as the Electronic Bearing Line (EBL) or the Variable Range Marker (VRM), and the number of times visual fixes were performed. The most relevant measurements were considered to be the use of visual fixes and the total interactions per minute.

Finally, situational awareness (SA) and Workload (WL) were also measured. To measure SA, at the end of each experiment, teams were requested to fill in the SART (Situational Awareness Rating Technique) (Annex V). It has 19 items on a 7-level scale, assessing demand, supply, and understanding. The final SA score is calculated through the formula: Understanding – (Demand – Supply).

On the other hand, to measure WL, teams filled in the Expanded NASA TLX (Task Load Index) questionnaire (Annex VI), which is made up of two different parts. In the first part, several pairs of dimensions are presented, from the following six: Mental Demand, Temporal Demand, Physical Demand; Frustration; Effort, and Performance. Participants are requested to choose, for each pair presented, what they believe to be the determining factor for assessing their task load.

The second part is a questionnaire made up of 12 items on a 20-level scale, which are then multiplied by 5 to obtain a 100-level scale. The first six items assess individual WL and give a direct result from 0 to 10 in the six aforementioned dimensions; then, each is weighted in the average according to the number of times it was selected in the first part. This gives a general Situational Awareness value, which was considered for analysis, as it factored in the importance given to each dimension by each participant. The other six items assess team WL in the following dimensions: Coordination Demand; Communication Demand; Time-sharing demand; team efficacy; team support, and team dissatisfaction. The answers to these last six items are not weighted. The last three dimensions were also selected for analysis, as they relate to the perception by each team member of their team in terms of efficacy, support, and satisfaction, which could be success factors for a better work environment and, therefore, more resilient navigation.

To assess performance, data was also collected from the NAVSIM Polaris instructor, the log of each bridge equipment, and the session recordings. After the pilot tests, the maximum distance from the route was considered insufficient as a sole performance measurement. A given team could have wandered completely off the route, endangering safety while remaining a relatively good average distance from it.

Therefore, the aforementioned performance data was also processed to provide the following indicators, representing the compliance of both time and positioning, selected in cooperation with the PTC specialists: Difference between ETA and ATA to the end; Difference between ETA and ATA for each wheel over point; Time on and off the route (with 50 yards tolerance) and both maximum and average distance to the route.

Following the definition of resilience provided in chapter 1, a resilient team is typically a team that can take a performance hit in a disruptive event and then quickly bounces back from it, as opposed to a team that continually degrades its performance. Yet, in the case of piloting, this common notion of a resilient team doesn't apply as the rigorous standards for positioning control don't allow for such a performance hit as other activities might.

Therefore, a resilient piloting team must be able to keep performing at the same level after the disruption. Not only that, but to be truly resilient, it must also have been able to detect and acknowledge the disruption and its impact. Otherwise, maintaining the performance level might not have been resilience but sheer luck.

A detection time of under three minutes was considered, as it is the average time interval between report cycles (preventing teams from reporting false information more than once). Such a combination of disruption detection and maintaining performance is what the study is aiming to find, as exemplified in the following figure.

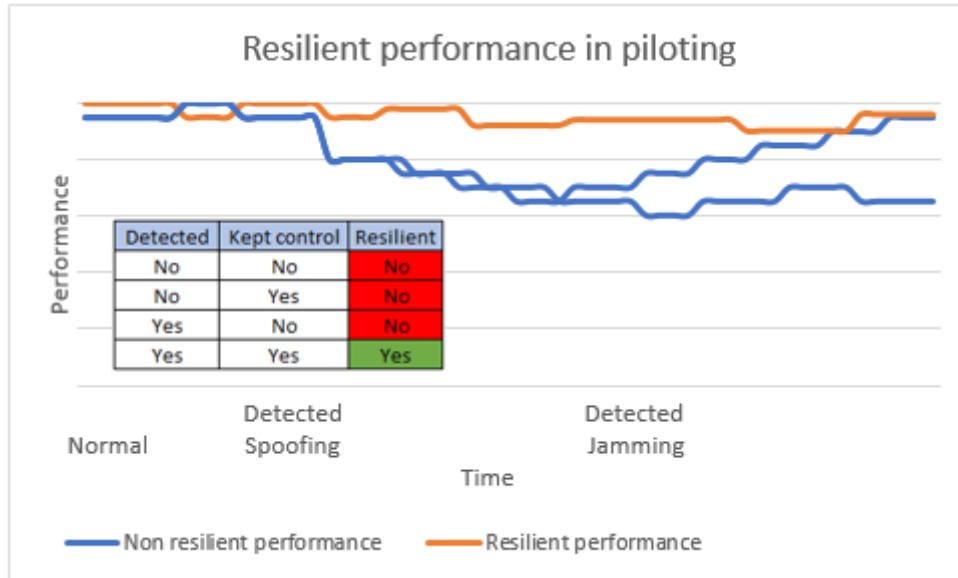


FIGURE 2.3: Resilient performance in piloting

Yet, these two criteria only cover two phases of the system states of the resilience wheel mentioned in Chapter 1: Alert, Emergency, and Restoration. Therefore, the other 2 (Recovery and Normal) must be analyzed to consider resilience in all its dimensions. Yet, the study’s methodology didn’t allow for these dimensions to be explored as there aren’t any recordings of the preparations, briefings, debriefings, and planning of the piloting teams. Therefore, these states will only be analyzed at an organizational level (the fleet as a whole).

Teams’ resilience will be assessed in terms of the Alert (through detection time), Emergency (through performance maintenance) and Restoration (in terms of the adaptations to the disruption). All three can be found in the performance sections. At the same time, the latter is also a part of the WAD vs. WAP analysis, which goes through the successful and unsuccessful adaptations and actions the different teams made while undergoing the disruptions.

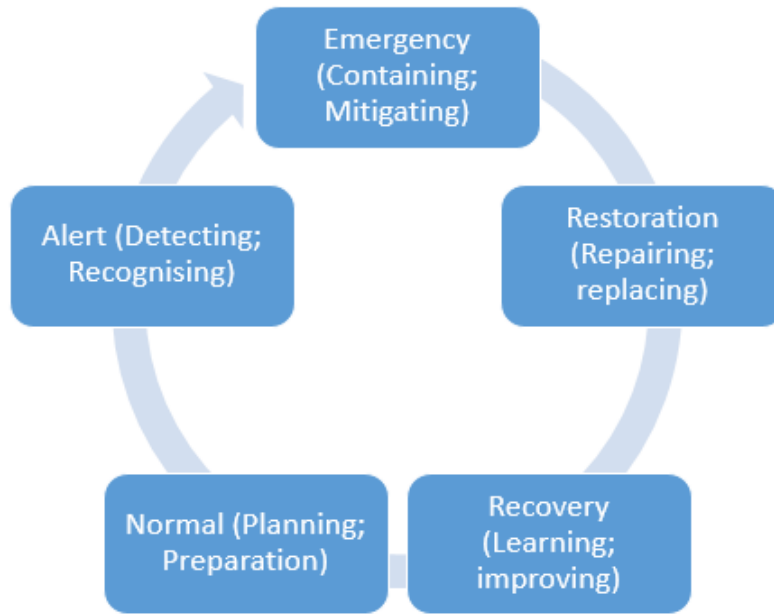


FIGURE 2.4: System states and functions of resilience

The pilot tests raised the possibility that compliance with procedures could also be a success factor in the team’s ability to attain superior positioning control, which means higher performance levels.

Therefore, to measure general piloting procedure compliance, the study group was given access to the checklists and reports used by the evaluators in each session, accounting for two main indicators. The first is global evaluation, a subjective performance result ranging from Below Standard to Very Good. The second is the number of aspects to improve (AtI), which can be categorized as critical, significant, and minor.

Yet, the occurrence of a GNSS disruption is not provided for in these documents, and it was hypothesized that the compliance to certain procedures (although they are currently not written in any navy doctrine document) in the face of one could again be a success factor for resilience.

Therefore, in cooperation with the PTC specialists, a post-disruption procedure checklist was elaborated (Annex VII) and divided into two categories. The first is Detection and communication (E.g., assessing if both spoofing and jamming were detected and communicated). The second is Impact Acknowledgment (E.g., assessing the acknowledgment of the impact of the disruptions on RADAR ARPA, AIS, and if the positioning source was changed on ECDIS).

2.3. Measurements

Except for the Trust in Automation questionnaire, which was only filled in by the ECDIS operator, chart plotter, and RADAR operator (as they operate or can operate with technology), all other questionnaires were filled in by all participants. Yet, the pilot tests showed that analyzing individual differences among all roles of the piloting teams wouldn't produce tangible contributions to answering the research questions.

Therefore, in Trust in Automation questionnaire, only the results from the ECDIS operators were analyzed. In contrast, on the remaining questionnaires, the analysis was performed with the average results for each team and the results for the NAVO's and ECDIS operators.

To provide an overview of the data collection process and the different data that will contribute to each category of measurements in the study, the following scheme summarizes data collection by category.

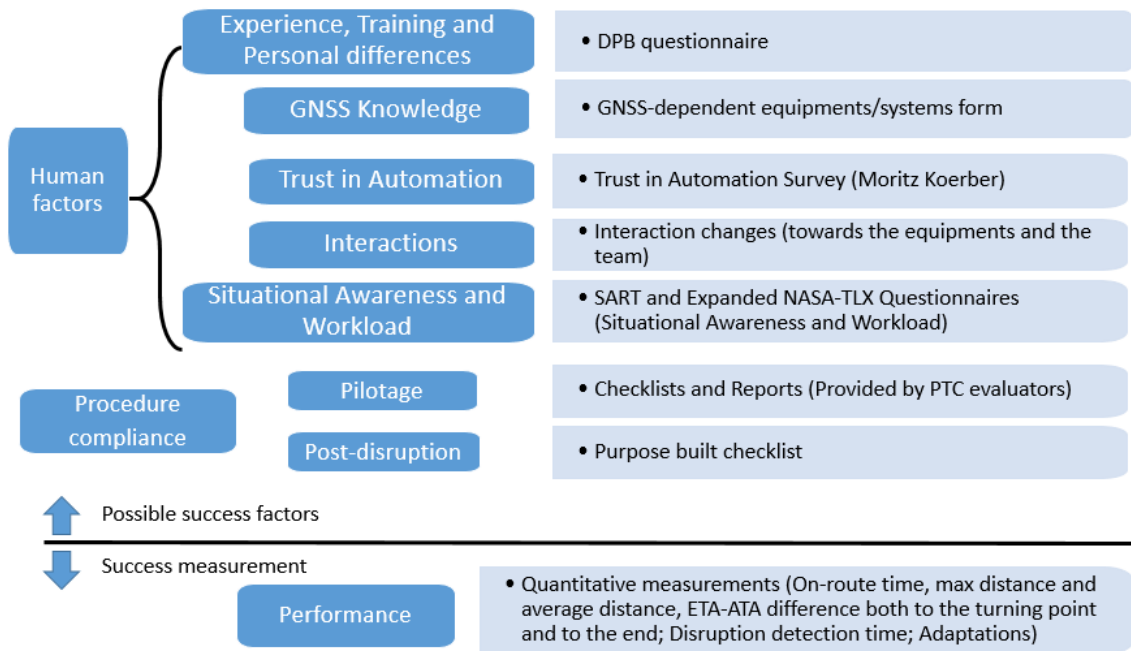


FIGURE 2.5: Data collection scheme by category

The following figure summarizes data collection time flux for the same purpose but intends to provide more of a chronological overview.

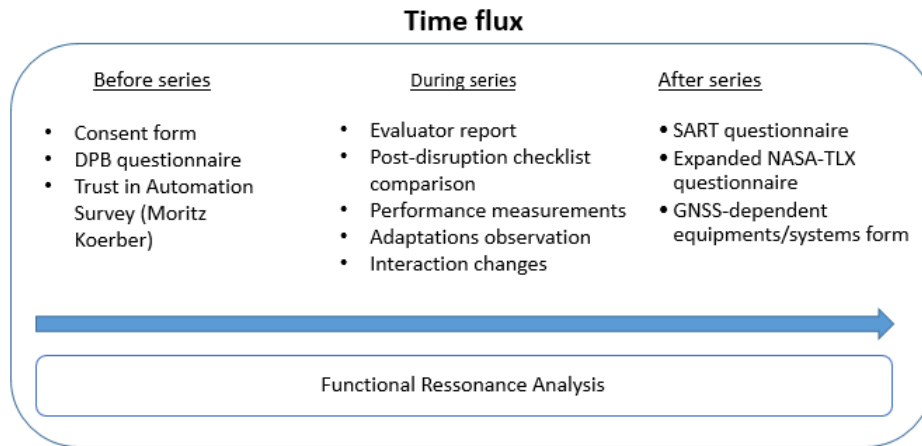


FIGURE 2.6: Data collection scheme by time

It should be noted that the pilot tests were the reason several of these measurements and tools were introduced. They either suggested leads to explore or revealed that certain measurements were insufficient or incomplete. Therefore, the measurements used in the pilot tests are significantly lower in quantity. The following figure summarizes data collection in the pilot tests.

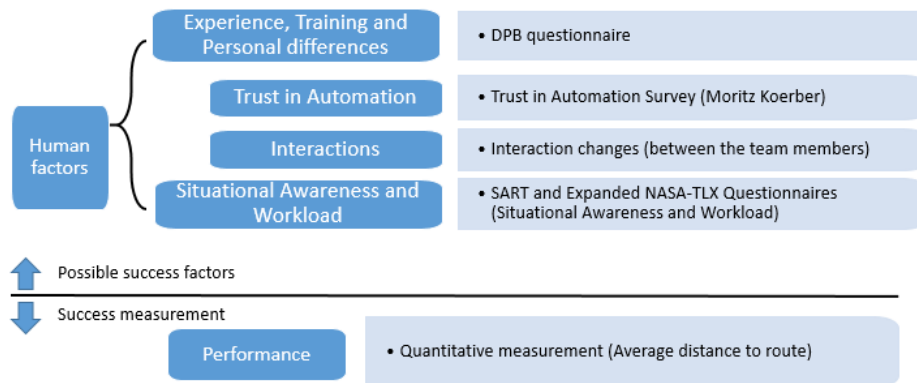


FIGURE 2.7: Data collection scheme by category of the pilot tests

The final protocol, in comparison with the pilot tests, introduces several new elements to the performance and procedure focused measurements, which are used for training and evaluation. These new elements include the introduction of knowledge-based human factors (GNSS-dependency of equipments/systems), as well as new quantitative performance assessment measurements (ETA-ATA difference to wheel over point and to the end, on-route time, maximum distance, disruption detection time and task adaptations). It also includes new procedure compliance measurements (piloting and post GNSS disruption), the measurement of interaction

changes with technology, and time on team and training analysis. The measurement of average distance to route, as well as the remaining human factors (Trust in automation, interaction changes with team members, situational awareness, and workload) remained unchanged.

This protocol can be further explored in the future and allow a complete assessment and measurement of the possible factors that can make the team perform better. Given the fact that each experiment required several preparations and actions to be performed by the author and the operator, a purpose-built checklist was written to ensure every experiment happened in equal circumstances according to the protocol, as well as allowing the use of newly developed capabilities in the future (Annex VIII)

Because it was expected that some participants might not have the required English proficiency to answer the questionnaires in that language, the GNSS-dependent systems/equipments questionnaire and the information leaflet were developed in Portuguese. The remaining documents were translated. The translation by Nepomuceno, 2020 was used for the Expanded NASA-TLX and SART questionnaires, and the author translated the Trust in automation questionnaire.

2.4 Technological considerations

The installation of the ECDIS equipment in the NAVSIM didn't account for its addition to the bridge's integrated navigation system. Therefore it becomes impossible to simulate disruptions and emergencies through the use of the dedicated functions of the Polaris Instructor for these situations.

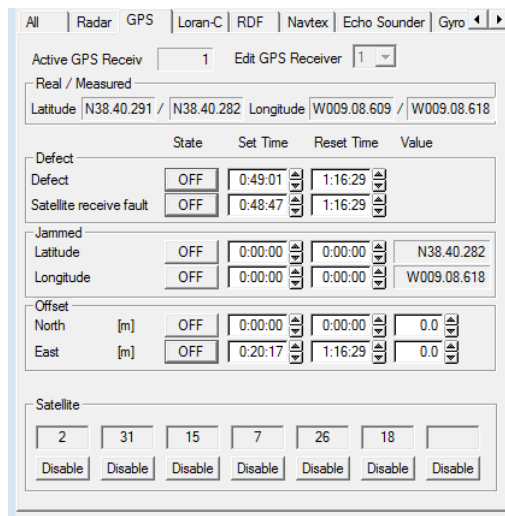


FIGURE 2.8: GPS fault options in Polaris Instructor

For example, if the jamming or spoofing option is activated in the instructor, it will appear in all bridge equipments except for the ECDIS. Given that this equipment is an essential part of the study, as its normal use is associated with GNSS signal usage, a different technological solution had to be adopted (Annex IX). The connection between the normal source of positioning and the ECDIS was changed to the server room, and a different computer was set up with a GPS simulator installed, the NMEA simulator v1.3.2 by Adrian Panaaj (Panaaj, 2022).

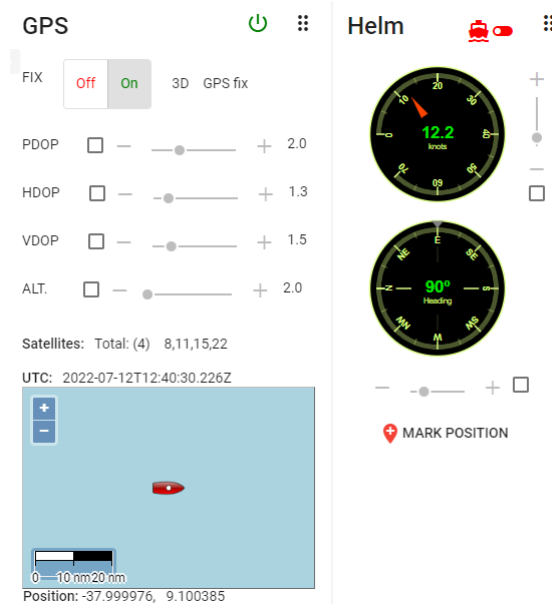


FIGURE 2.9: NMEA Simulator positioning control

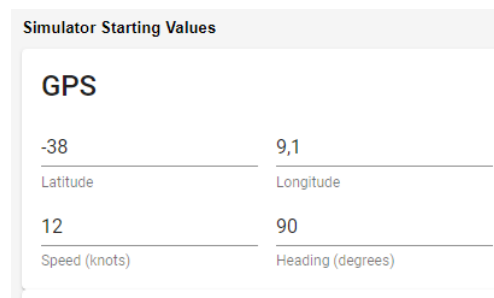


FIGURE 2.10: NMEA Simulator starting values

Spoofing was set for a 600m difference West of the position when the disruption was introduced. Before commencing, the initial parameters were introduced in the NMEA simulator (which takes an average time of 2 minutes). At the same time, the spoofing (offset) option was activated in the NAVSIM, the GPS signal simulation was initiated, and the positioning source was manually switched in the server room from the ECDIS GPS to the NMEA simulator input.

The spoofing feature in the Polaris Instructor can be activated by defining an offset value and direction (from the true position). Yet, there is no such option in the NMEA simulator. Therefore, for the spoofing solution to be the same in the ECDIS and the rest of the bridge, a Python script had to be written (Annex X).

This script takes in the current coordinates, heading, and speed, as well as the offset value and direction intended. It then makes a two-step calculation of the final spoofing position to be introduced in the NMEA simulator (which corresponds to the spoofing position in the Polaris Instructor).

The final hardware and software technological solution also constitute a new capability that the PTC can further explore in the future as a way to simulate GNSS failure or tampering in ECDIS.

The following figure provides the expected changes in precision of GPS, DGPS, the Gyro, and the use of visual fixes throughout all three stages of the study: normal availability, spoofing, and jamming.

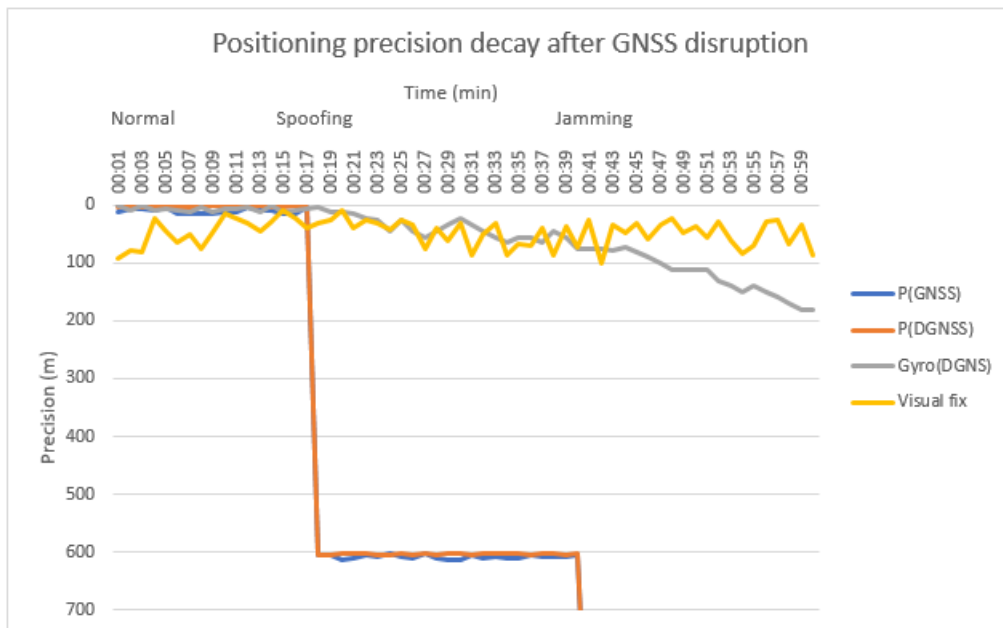


FIGURE 2.11: Expected precision of different equipments and methods throughout the experiments

In addition, given that spoofing and jamming disruptions were introduced both in the ECDIS and the integrated navigation system, it becomes impossible to measure the ship's positioning by using solely the log from the ECDIS or the GPS.

To overcome this limitation, the route of each team was previously introduced in the Polaris instructor (which, despite the disruptions, continues to show

the true position of the vessel). The operator permanently registered the distance between the ship and the route throughout the session.

A summary of data collection and processing numbers can be seen in the following figure.

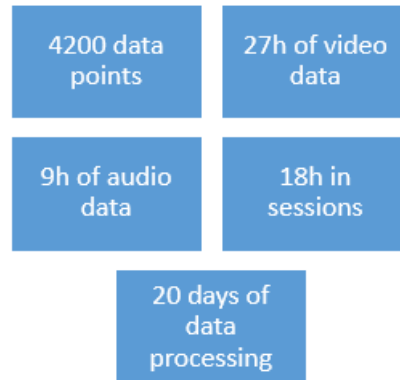


FIGURE 2.12: Data collection and processing summary

2.5 Limitations

The first limitation of the study was the previously mentioned fact that the ECDIS equipment was not integrated into the bridge as was the rest of the equipments, resulting in the fact that the faults introduced in the instructor didn't affect it. Although this issue was circumvented through a purpose-built technological solution, it still involved extra resources in starting and maintaining the disruption (mainly spoofing).

Some of the questionnaires used, namely SART, Expanded NASA-TLX, and TiA, are based on self-assessment, meaning that they are based on the subjective view of each participant of their Situational Awareness, Workload, and Trust in Automation, respectively.

During the time window of the study for data collection (Between April and May), there was an unusual unavailability of naval units in the base with enough team members to participate in the study. This resulted in the window being extended until the 13th of July to obtain 6 data collection sessions.

For the same reason, the teams that were available and took part in the study all faced the unavailability of some members of the piloting team, including some key elements such as the chart, ECDIS, or RADAR operators. In this period,

the NAVSIM was also closed for maintenance for two weeks. The use of the evaluator's reports and checklists was limited to two sessions due to staff unavailability in the remaining sessions.

While the navigation simulator has the advantages of being a risk-free and controlled environment, teams had to rely primarily on visual data. This data, in the NAVSIM, was relatively different from what it would be in a real situation, not only in the appearance of certain marks but also in the field of visibility from the bridge. The same happens with the layout of the bridge equipments and the equipments themselves, which can be significantly different in some ships of the Portuguese navy.

The participants were from different classes of ships, meaning that the organization and procedures of the piloting teams may vary between them, as may vary the brand of the equipments used and, therefore, their operation.

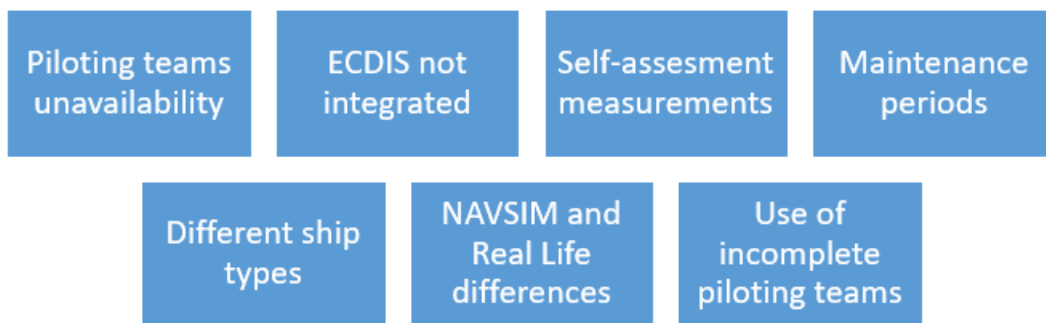


FIGURE 2.13: Summary of the study's limitations

2.6 Summary

This chapter starts with the connection between the literature review, the chosen research questions, and the study design. It describes the scenario that was used, the type of training, the timeline, and the sequence of actions of the experiment. It describes the study's sample and explains that pilot tests took place before the experimental study to validate the protocol and improve the methodology. It mentions that the study required approval from the Portuguese Naval Fleet Command and coordination meetings.

It goes into detail explaining each measurement and the tools used, providing two figures of data collection summaries. Next, it mentions that the NAVSIM of the PTC had some limitations in simulating jamming and spoofing. Therefore

several technological adaptations were performed to allow a correct and synchronous disruption simulation in all bridge equipments, continuing with a summary of the raw data collection and its processing.

The chapter finishes with the limitations of the study, which besides the already mentioned technological difficulties, include the general unavailability of piloting teams, NAVSIM maintenance, staff shortage, the differences between SBT and real life, and the use of different ship types.

Chapter 3

Results

3.1 Piloting model building

3.1.1 Representation of work and bottlenecks

Building on this idea of the importance of understanding the difference between work as prescribed and work as done, a FRAM model of piloting as prescribed was developed. It allows the study of possible bottlenecks beforehand for any given situation. In this case, the analysis will focus on a GNSS disruption.

This FRAM model, by reflecting the prescribed procedures, can also allow the comparison with what happened throughout the study, meaning work as done, therefore studying the differences and similarities. For this purpose, qualitative data was collected through the analysis of the video and audio recordings and notes taken during the experiments.

The FRAM model was built entirely based on what is prescribed in the navigation doctrine of the Portuguese navy, namely in the publication *Instruções de Navegação da Armada 4* (Estado-Maior da Armada, 2008). In order to allow the broadest possible assessment, the model includes all preparations, procedures and human and material resources, as well as the control elements. Since the mapping was extensive, the model includes 54 functions. For this reason, it is available in annex XI.

Blue functions are preparations, representing everything that must be done before the moment piloting begins. They involve all the parameters of a port study. This means incorporating the Commander's Navigation Standards, defining and plotting the route, and visual and RADAR aids. It also means factoring in meteorological, oceanographic, and vessel traffic information.

Red functions are related to positioning and navigation control. They are associated with the prescribed doctrine standards for navigation and compliance with the navigation and communication procedures, such as performing dead reckoning. The majority of the functions involve performing the prescribed reports: ETA, speed and heading corrections, sounding, available waters, route compliance, as well as distance and time to the next wheel over point.

Yellow represents supporting functions. These functions supply the piloting teams' human resources, and information needs to assure proper compliance with the set procedures. Namely, this entails: Having all team members available and ready, monitoring the equipments alarms, using their adequate settings, calculating their errors, registering wind and current information, and remaining vigilant for collision avoidance.

3.2 Pilot tests

The goal of the pilot tests was to validate the protocol, consolidate the preparations, procedures, and sequence of events, and also provide analysis examples that could become interesting leads for new measurements or tools to add to the methodology.

3.2.1 Navigation

The pilot tests' performance was assessed only in terms of the average distance from the route in each leg. The less the average distance, the better the performance. The use of the average as a sole measurement of positioning control was found to be a limitation. In the example of the following figure, it can't truly be said that team a) performed worse than team b), that wandered continuously from Port to Starboard, and team c) that was completely off the route at the beginning and end of the route.

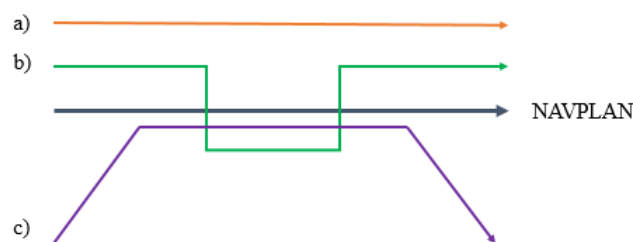


FIGURE 3.1: Measurement visualization - Average distance from route

Yet, they both had a lower average distance to the route. The average distance was measured in yards, with the lower values indicating better performance.

Team	Average distance		
	1st leg	2nd leg	Average
Team A	175	200	187,5
Team B	150	350	250
Team C	150	250	200

TABLE 3.1: Performance results in the pilot tests presented in yards

Team A was the better performer on average with 187.5 yards of average distance, although they were the worst performers in the first leg, even if only by 25 yards. Yet, as they recorded only a 25 yards difference between the 1st and the 2nd leg, they were the best average result. It should be noted that there was an increase in the average distance to the route after the disruption, between 25 and 200 yards.

3.2.2 Human factors

3.2.2.1 Trust in Automation

Between the parameters measured in the Trust in Automation questionnaire, as mentioned in the previous chapter, Trust in Automation, Propensity to Trust, and Reliability were considered for analysis. The values come from the average of the answers on a Likert Scale, ranging from Strongly Disagree (1) to Strongly Agree (5). A higher value represents a higher level of each parameter, which is suggested by literature as a precursor to worse performance.

	Reliability/Competence	Propensity to Trust	Trust in Automation
Team	Score		
Average A	3,2	2,5	3,0
Average B	3,8	3,2	4,2
Average C	3,4	2,7	4,0

TABLE 3.2: Table with the average results for the Trust in Automation questionnaire for the pilot tests

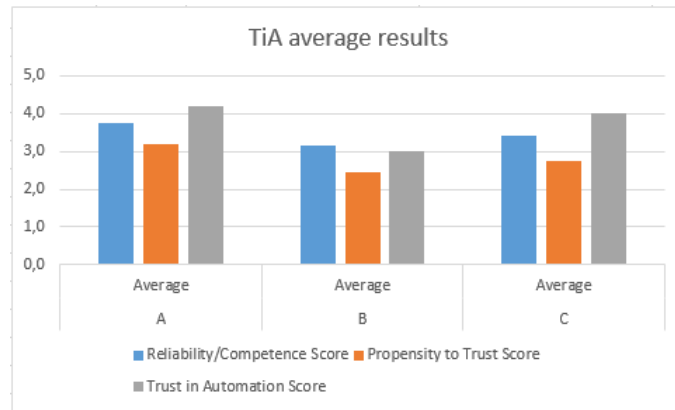


FIGURE 3.2: Chart with the average results for the Trust in Automation questionnaire for the pilot tests

Team A registered lower average indicators in the three parameters considered, followed by team C, with team B registering the higher levels, on average, in all parameters between the three.

Team	Function	Reliability/Competence Score	Propensity to Trust Score	Trust in Automation Score
A	ECDIS	2,5	1,7	1,5
B	ECDIS	3,8	3,3	4,0
C	ECDIS	3,3	2,3	4,0

TABLE 3.3: Table with the ECDIS operator's results for the Trust in Automation questionnaire for the pilot tests

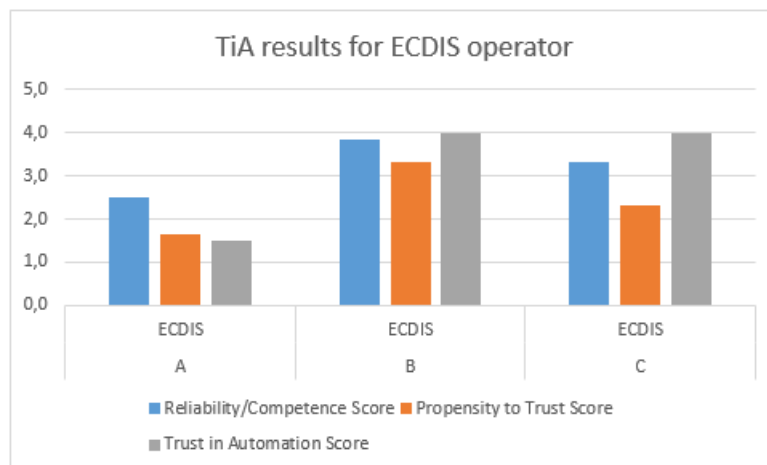


FIGURE 3.3: Chart with the ECDIS operator's Trust in automation questionnaire results for the pilot tests

The same tendency was expressed in the results of the ECDIS operator, with team A scoring the lower results, followed by team C and B.

3.2.2.2 Interactions between team members

Behavior and number of interactions can be best understood by having in mind the spatial distribution of the different workstations. In the NAVSIM there isn't a dedicated communication circuit for information flow within the piloting team. Therefore all communication is done simply by word of mouth. The NAVSIM's bridge layout can be seen in the following figure.

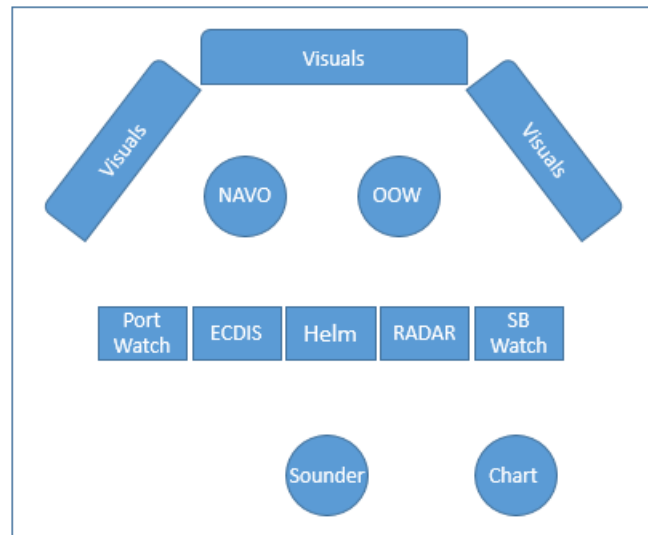


FIGURE 3.4: NAVSIM's bridge layout

Concerning the interactions between each team member, every single interaction between each member was accounted for and registered in two main categories: report cycles and single interactions. Within the report cycles, they could be registered as complete or incomplete, depending on whether all prescribed participants reported information. An example of the coding used can be seen in the following figure.

Team A			
Interaction	1st leg	2nd leg	Total
Complete sequence	6	0	6
Incomplete sequence	1	2	3
NAVO-ECDIS	2	2	4
NAVO-RADAR	0	0	0
NAVO-Chart	2	3	5
ECDIS-RADAR	2	1	3
ECDIS-Chart	0	0	0
ECDIS-Watch	0	0	0
RADAR-Chart	0	0	0
Total single interactions	6	6	12

TABLE 3.4: Number of interactions between team members results in Team A

Since there wasn't any group of single interactions between two specific team members worth studying in more detail, the results are displayed in terms of their average. Team A registered the higher number of single interactions, followed by team C and team B having the lower registry.

The total number of reporting cycles performed was relatively similar between all the teams, with team B registering the higher number of complete report cycles due to the fact that they didn't detect the spoofing and therefore continued to use the ECDIS equipment in the report cycles.

Team A			
Interaction	1st leg	2nd leg	Total
Complete sequence	6	0	6
Incomplete sequence	1	2	3
Total single interactions	6	6	12
Team B			
Interaction	1st leg	2nd leg	Total
Complete sequence	6	3	9
Incomplete sequence	0	0	0
Total single interactions	4	4	8
Team C			
Interaction	1st leg	2nd leg	Total
Complete sequence	5	1	6
Incomplete sequence	2	3	5
Total single interactions	5	5	10

TABLE 3.5: Number of interactions between team members results

3.2.2.3 Situational Awareness

In Situational Awareness (SA), compelling differences were found in the average SART results. The values come from a formula based on the answers on

3.2. Pilot tests

a Likert Scale, ranging from Low (1) to High (7). This composite result can range from -14 to 46. The formula used is presented in Chapter 2.

A higher value represents a higher level of Situational Awareness, which in turn is suggested by literature to be a precursor to a better performance. Of the different teams, team A recorded the higher score, followed by team C and team B.

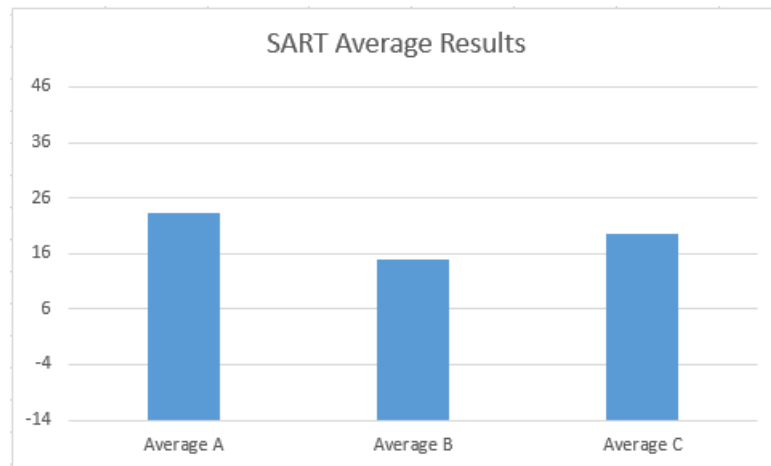


FIGURE 3.5: Chart with the average SART results for the pilot tests

The same could be observed for the NAVO, in which team A again recorded the higher levels, followed by teams C and B.

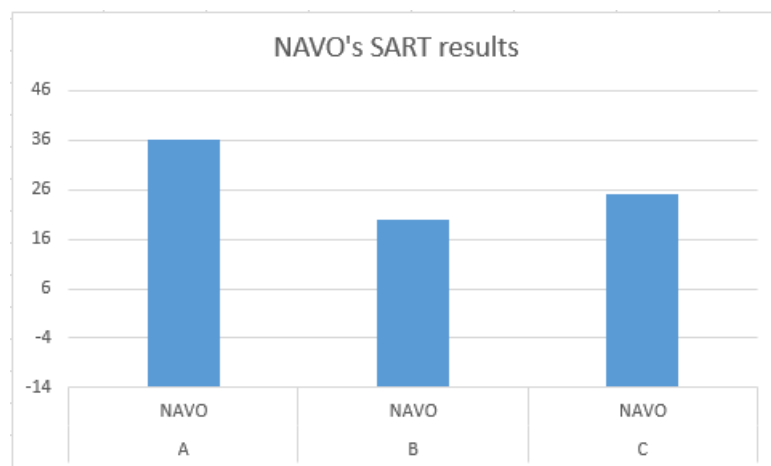


FIGURE 3.6: Chart with the NAVO's SART results for the pilot tests

As for the ECDIS operators, the opposite was true, with team B registering the higher value followed by teams C and A.

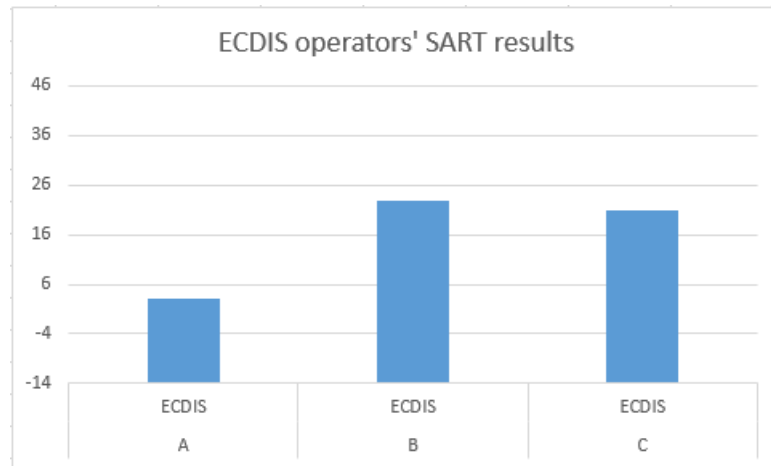


FIGURE 3.7: Chart with the ECDIS operators' SART results for the pilot tests

3.2.2.4 Individual and team workload

When it comes to individual and team workload, they were assessed through the Expanded NASA-TLX questionnaire. The values for individual Workload come from a formula based on the Likert Scale answers, ranging from Very Low (1) to Very High (20). This composite result can range from 5 to 100. The formula used is presented in Chapter 2.

A higher value represents a higher level of Workload, which in turn is suggested by literature to be a precursor to worse performance. When it comes to team workload, each answer should be interpreted separately and the ones chosen for analysis were team efficacy, team support and team dissatisfaction. The values are directly based on the answers on a Likert Scale, ranging from Very Low (1) to Very High (20).

There couldn't be found any literature relating each answer to team workload questions to performance. Yet, higher levels of team support and effectiveness are generally correlated with better performances and higher levels of team dissatisfaction with worse performances (Kim et al., 2020).

Regarding individual Workload, team C registered the higher values of the ECDIS operators and NAVOs but the lower average value. It also registered higher values in team efficacy and supportiveness, but again not on average, with team B registering the higher values for such. The results for team dissatisfaction were highly varied, depending mainly on the function, with the average values being very low, specially in team C.

Team	Function	Weighted TLX	Team efficacy	Team support	Team dissatisfaction
A	ECDIS	22,7	16	4	10
B	ECDIS	67,0	12	14	2
C	ECDIS	76,3	18	20	10
A	NAVO	46,0	15	7	2
B	NAVO	59,7	18	18	9
C	NAVO	91,3	18	17	7
Average A		69,5	14,0	14,2	3,4
Average B		70,2	14,8	14,4	2,9
Average C		67,6	14,4	13,7	2,3

TABLE 3.6: Table with the results of the Expanded NASA-TLX questionnaire

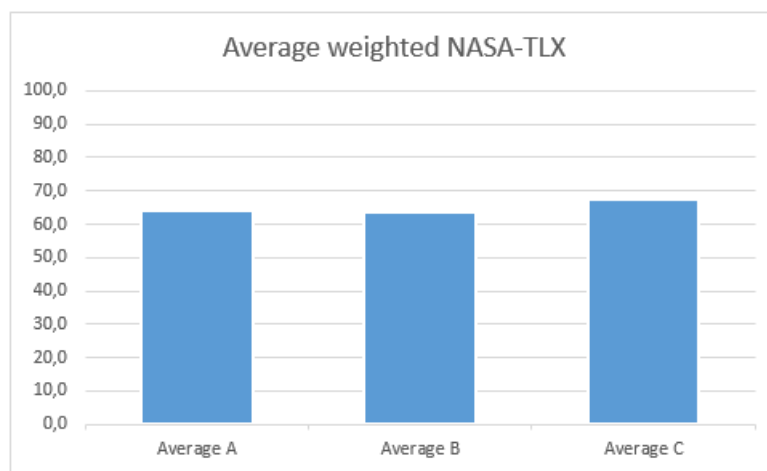


FIGURE 3.8: Chart with the results of the weighted NASA-TLX in the pilot tests

3.3 Experimental study

3.3.1 Navigation

When it comes to the detection of the disruptions, all teams detected spoofing and jamming within 3 minutes. The only exception was team E which after spoofing reported the false position throughout the leg, with a detection time of 9 minutes. The less the detection time, the better.

Team	Spoofing detection time	Jamming detection time
D	2 min	Immediate
E	9 min	2 min
F	2 min	Immediate
G	Immediate	Immediate
H	Immediate	Immediate
I	Immediate	Immediate

TABLE 3.7: Detection time

Contrary to the pilot tests, performance was measured in two dimensions: control of time and control of positioning. In terms of time control, the ETA-ATA difference to the wheel over point and to the end were measured. The objective is for teams to have the least possible difference.

The ETA-ATA to the wheel over point difference was very similar across all teams, between 1 and 2 minutes, except for team F, which recorded an average difference of only 15 seconds. Concerning the difference in the wheel over points performed in normal navigation and in spoofing or jamming, there were no clear differences.

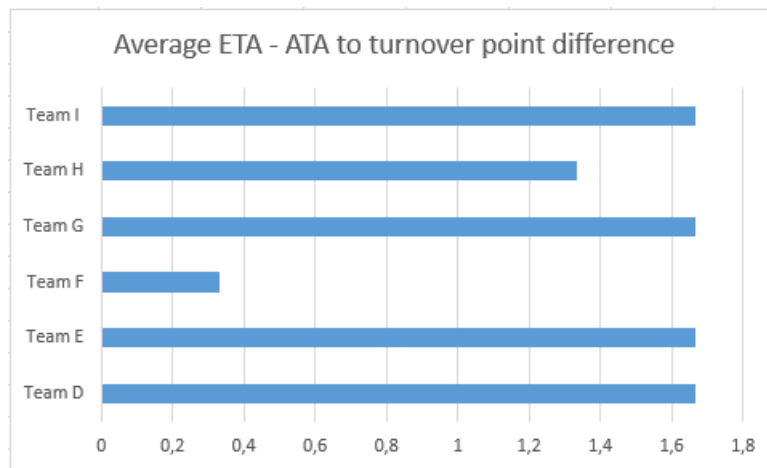


FIGURE 3.9: Chart with the ETA-ATA to wheel over point difference in minutes

Yet, when it comes to the ETA-ATA to the end difference, even though the F team is still the standout, it is so for the opposite reason, it registered a significantly higher value of 10 minutes, while the other teams were between 2 and 5 minutes. This happened because, in the final leg, which is not considered for the average difference, the team went entirely off the route and took considerable time getting back to it, therefore arriving 10 minutes late.

3.3. Experimental study

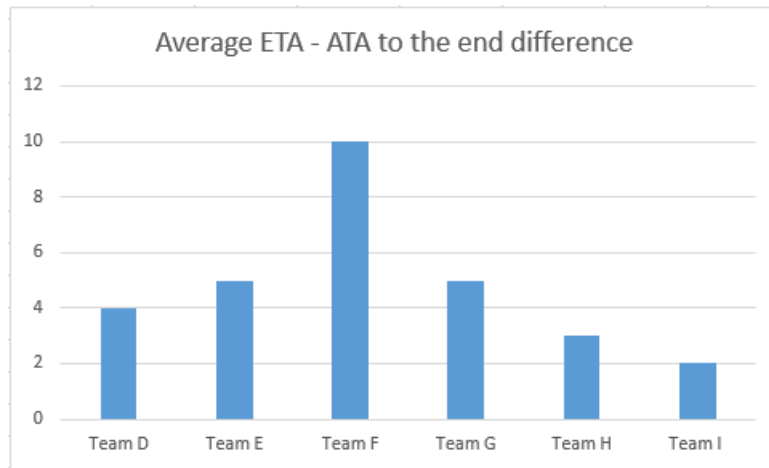


FIGURE 3.10: Chart with the ETA-ATA to the end difference in minutes

Regarding controlling positioning, overcoming some of the limitations in the pilot tests, three measurements were adopted: Average and maximum difference from the route, as well as the percentage of time within 50 yards of the route. The less the average and maximum differences, the better the performance. The more time within the route, the better the performance.

Regarding average distance from the route, half of the teams presented expressive differences between normal navigation and either spoofing or jamming. On average, the distance went up between 60 and 80 percent while undergoing GNSS disruptions, although with relatively small values.

	Normal	Spoofing	Jamming
Teams average	51	83	93
D	89	229	124
E	33	142	55
F	46	21	253
G	71	24	74
H	34	23	14
I	32	58	41

TABLE 3.8: Table with the average distance to the route results in yards

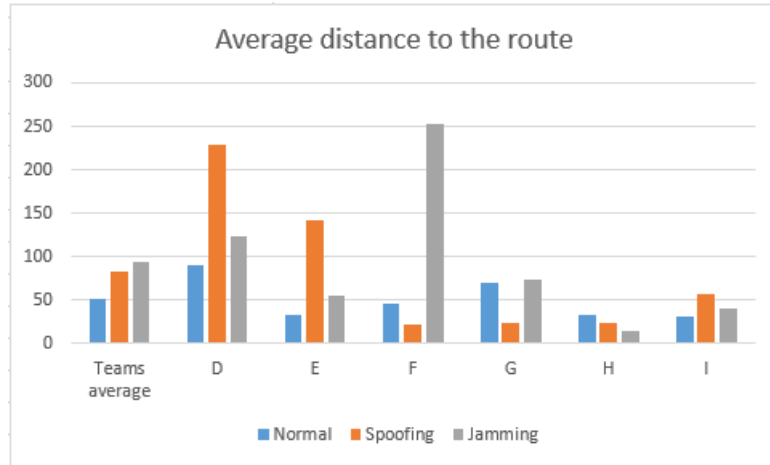


FIGURE 3.11: Chart with the average distance to the route results in yards

The same tendency was noticeable in terms of the maximum distance from the route, although the average was affected by the outlier of team F which recorded a value of 830 yards for the reasons aforementioned.

	Normal	Spoofing	Jamming
Teams average	111	138	276
D	142	365	405
E	120	240	100
F	101	61	830
G	122	41	142
H	100	40	80
I	80	80	100

TABLE 3.9: Table with the maximum distance to the route results in yards



FIGURE 3.12: Chart with the maximum distance to the route results in yards

3.3. Experimental study

On the other hand, the average percentage of time on the route displayed a high variation between the participant teams, with some even showing higher values while undergoing GNSS disruptions.

	Normal	Spoofing	Jamming
Teams average	67	58	64
D	17	0	63
E	83	16	50
F	79	100	54
G	50	100	38
H	79	100	96
I	95	32	85

TABLE 3.10: Table with the average percentage of time on the route results

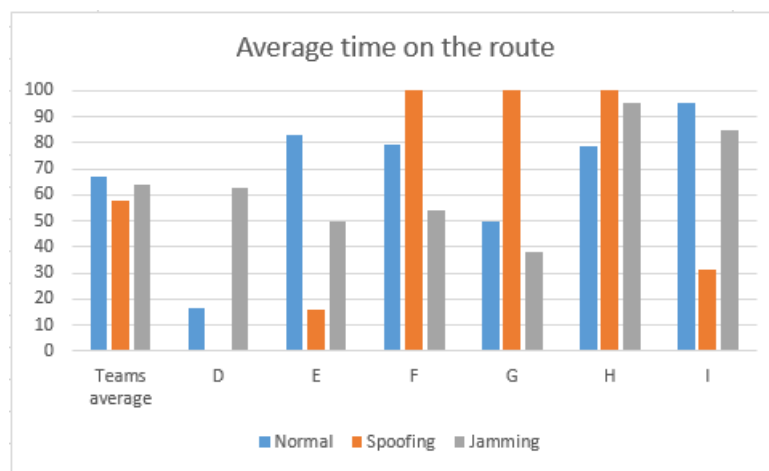


FIGURE 3.13: Chart with the average percentage of time on the route results

The average results for each team in each positioning performance measurement show some compelling differences between the participants. Only team H and I are above average in every measurement (the above-average results are highlighted in green).

	Average distance	Maximum distance	Time on track
Team D	164	142	70
Team E	155	405	29
Team F	58	240	59
Team G	76	100	49
Team H	42	100	74
Team I	23	29	91
Average	71	169	62

TABLE 3.11: Average results for each team for all positioning performance measurements

Finally, when it comes to the different adaptations that were made by the teams in response to the GNSS disruptions, which are extensively described at the beginning of the next chapter, they were all mainly related to the ECDIS operator. 4 categories of decision were identified: Whether it should remain in station; Whether it should report; If yes, based on the wrong GPS information (with the NAVO filtering it out); Or based in the visual fixes' information. The following results were obtained.

Team	On station	Reporting	Intentionally reported GPS	Reported fixings instead
D	No	No	No	No
E	No	No	No	No
F	Yes	No	No	No
G	Yes	Yes	Yes	No
H	Yes	Yes	No	Yes
I	Yes	Yes	No	Yes

TABLE 3.12: Adaptations to the GNSS disruption performed by each team

3.3.2 Human factors

3.3.2.1 Time on team and Training

Regarding the demographic, time on the team, and training information presented in Chapter 2, since there weren't any clear differences in demographics between the teams, the other two factors remained that could be success factors for more resilient navigation.

Question	Team						Total	Stand. Dev	Max	Min
	D	E	F	G	H	I				
Time on current team (months)	12,0	5,4	7,6	8,1	11,0	7,1	8,8	2,3	12,0	5,4
Months since last full training plan	42,0	78,0	20,0	24,0	2,0	2,0	33,2	26,2	78,0	2,0
Number of SIMPILOTEX's in 2022	11,0	6,0	2,0	2,0	6,0	14,0	5,4	4,4	14,0	2,0

TABLE 3.13: Experience and training data

The average time on the piloting team was relatively low, at approximately nine months. Team D and H are the teams with more experience working together, with 12 and 11 months, respectively.

As for months since the last full training plan the average is high, over two years and a half, although it is affected by the results of team D and E which didn't perform a full training plan for several years. Team H and I stand out because they completed a full training plan only two months ago.

Regarding the number of PILOTEX exercises performed on the NAVSIM this year, teams D and I performed the higher number with 11 and 14, respectively. Teams F and G performed the lower number with only two exercises each.

3.3.2.2 GNSS Knowledge

Concerning the results of the GNSS-dependent equipments/systems form, all teams could correctly identify the AIS and ARPA. The higher the number of correct answers, the more theoretical knowledge of the GNSS signal usage in the bridge equipments.

In terms of the general number of correct answers, team H and I recorded the higher amount on average, as well as among NAVO's and ECDIS operators', although the differences to the rest of the sample were not very expressive.

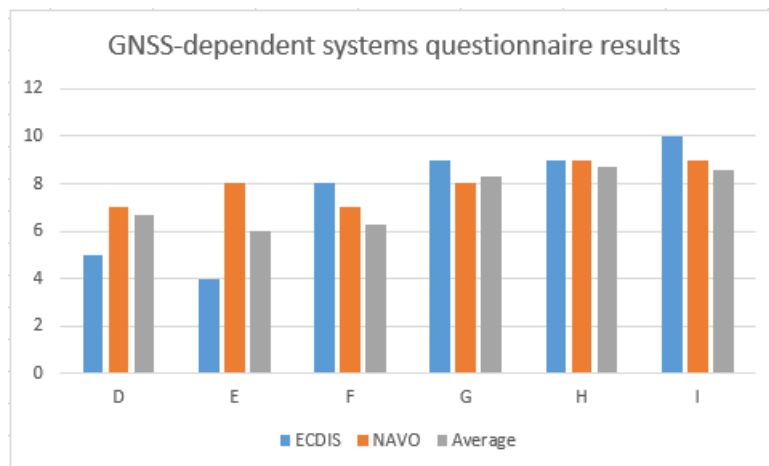


FIGURE 3.14: Results of the GNSS-dependent equipment/systems form - Number of correct answers

3.3.2.3 Trust in Automation

Among ECDIS operators, teams D and G recorded the lower values of reliability, teams F and I the lower values of Propensity to Trust, and teams E and I recorded the higher values of general Trust in automation. Therefore, there wasn't any clear tendency on the first two parameters, and the results in the last one were very similar to each other.

The values come from the average of the answers on a Likert Scale, ranging from Strongly Disagree (1) to Strongly Agree (5). A higher value represents a higher level of each parameter, which is suggested by literature as a precursor to worse performance.

		Reliability/Competence	Propensity to Trust	Trust in Automation
Team	Function	Score	Score	Score
D	ECDIS	3,3	3,3	4,0
E	ECDIS	4,0	3,3	4,5
F	ECDIS	3,7	2,0	4,0
G	ECDIS	3,3	2,7	4,0
H	ECDIS	3,8	3,0	4,0
I	ECDIS	3,8	2,3	4,5

TABLE 3.14: Table with the Trust in automation questionnaire results for the ECDIS operators

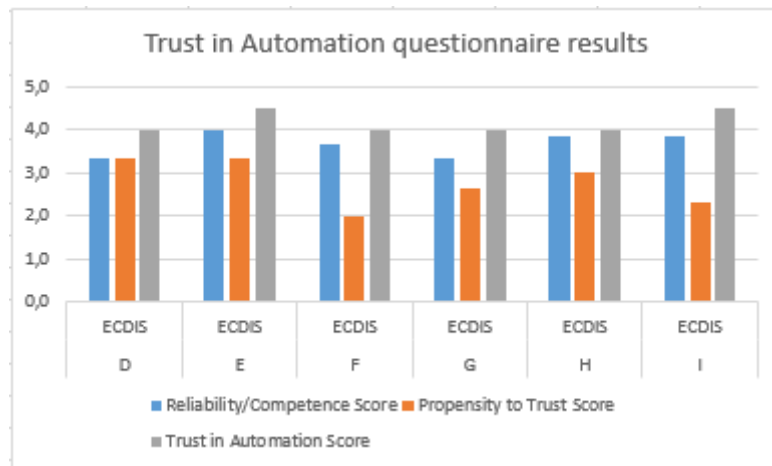


FIGURE 3.15: Chart with the Trust in automation questionnaire results for the ECDIS operators

3.3.2.4 Interactions between team members

Following the same coding used in the pilot tests and therefore registering the number of interactions between every single team member throughout the experiments, the data were processed to obtain valid indicators for use in the analysis, which had to be reduced to a common time reference, in this case, the minute.

For a better spacial perception of how the interactions took place, a figure with the bridge layout can be seen in the equivalent subsection of the pilot tests. It should be recalled that in the NAVSIM, there isn't a dedicated communication circuit for information flow within the piloting team. Therefore all communication is done simply by word of mouth.

NAVO interactions/min				ECDIS interactions/min			
Team	Normal	Spoofing	Jamming	Team	Normal	Spoofing	Jamming
D	0,7	0,3	1,0	D	0,4	0,1	0,3
E	0,2	0,5	0,3	E	0,3	0,6	0,2
F	0,4	0,3	0,6	F	0,2	0,2	0,2
G	0,3	0,6	0,4	G	0,2	0,2	0,2
H	0,0	0,3	0,1	H	0,1	0,3	0,3
I	0,4	0,1	0,3	I	0,1	0,3	0,1
Single interactions/min				Report cycles/min			
Team	Normal	Spoofing	Jamming	Team	Normal	Spoofing	Jamming
D	0,9	0,6	1,6	D	0,2	0,2	0,2
E	0,4	0,8	0,4	E	0,4	0,2	0,1
F	0,4	0,5	0,9	F	0,3	0,3	0,1
G	0,5	0,8	0,8	G	0,1	0,2	0,2
H	0,2	0,4	0,3	H	0,2	0,2	0,2
I	0,4	0,4	0,5	I	0,2	0,3	0,2

TABLE 3.15: Interactions between team members results

There was a general spike in single interactions while undergoing the GNSS disruptions, with team H and I remaining more constant. Regarding report cycles/min, most teams maintained a steady rhythm throughout the experiment except for teams E and F, which registered a drop in the frequency of their reports.

The ECDIS interactions/min registered a high variation between the different teams, with teams F and G maintaining the rhythm, team D dropping, and teams E, H, and I registering a spike. The same tendency could be observed in the NAVO interactions/min with teams D, F, and I dropping the rhythm while undergoing spoofing, contrary to teams E, G, and H that stepped it up.



FIGURE 3.16: Interactions between team members results

3.3.2.5 Interactions with technology

When it comes to interactions with technology, the coding used was based on the most used tools on the ECDIS equipment. Following the same principle used for team interactions, the data had to be reduced to a common time reference, in this case, the minute, to obtain valid indicators for use in the analysis. An example of the coding can be found in the following figure, representing the interactions with the ECDIS equipment for team D.

Team D			
ECDIS			
Interaction	Normal	Spoofing	Jamming
Menus	5	4	0
Zoom change	5	0	0
Contact information	0	0	0
Obtained position through azimuths	4	0	0
EBL/VRM	4	0	0
Total	18	4	0
Total/min	1,4	0,2	0,0

TABLE 3.16: Interactions with ECDIS results for team D

As mentioned in the previous chapter, the use of visual fixes and the total interactions per minute were chosen for analysis. Regarding the first, teams D and E started using fixes as prescribed but slowed down or stopped using them entirely when undergoing the GNSS disruptions. Team F and G never really used fixes (team G used them once at the beginning of the experiment), and team H and I used them throughout the experiment.

ECDIS - Obtained position through fixings			
Team	Normal	Spoofing	Jamming
D	4	0	0
E	4	2	1
F	0	0	0
G	1	0	0
H	5	5	3
I	5	3	6

TABLE 3.17: ECDIS fixes use results

Regarding the total number of interactions per minute, all ECDIS operators progressively declined their number of interactions with the equipment as the experiment, and the disruptions went on. The exception was team H and I, which kept a similar rhythm throughout the experiment (team H) or even interacted more with the equipment as the experiment continued (team I).

ECDIS - total interactions/min			
Team	Normal	Spoofing	Jamming
D	1,4	0,2	0,0
E	0,5	0,4	0,2
F	0,6	0,6	0,1
G	0,3	0,2	0,1
H	0,6	0,5	0,5
I	0,3	0,4	0,6

TABLE 3.18: Table with total interactions per minute between the ECDIS operator and the equipment

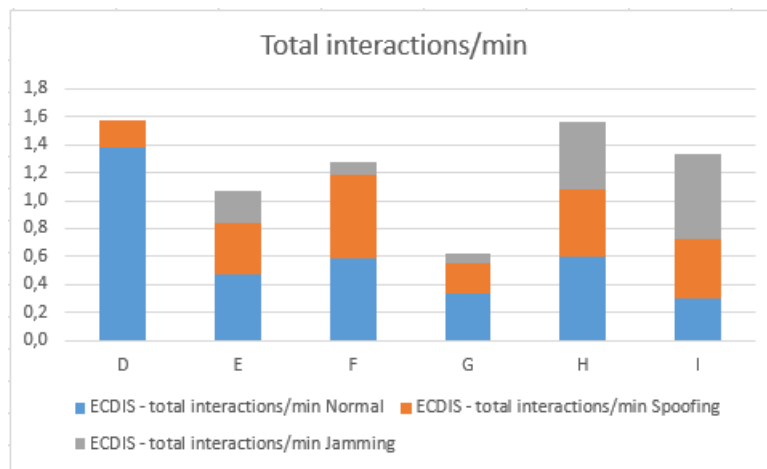


FIGURE 3.17: Chart with total interactions per minute between the ECDIS operator and the equipment

3.3.2.6 Situational Awareness

Regarding Situational Awareness, the results of the SART questionnaire were very similar across the different teams. This happened with the ECDIS operators and NAVOs, as well as on average. The values come from a formula based on the answers on a Likert Scale, ranging from Low (1) to High (7). This composite result can range from -14 to 46. The formula used is presented in Chapter 2.

A higher value represents a higher level of Situational Awareness, which is suggested by literature as a precursor to better performance. Team G and E recorded the higher result on ECDIS operators, while team E and I recorded the higher results among NAVOs and on average.

TEAM	SART Results		
	ECDIS	NAVO	Average
D	18	23	21,1
E	20	30	23,7
F	17	18	22,3
G	23	23	21,2
H	19	20	21,2
I	18	31	24,5

TABLE 3.19: Table with the results of the SART questionnaire

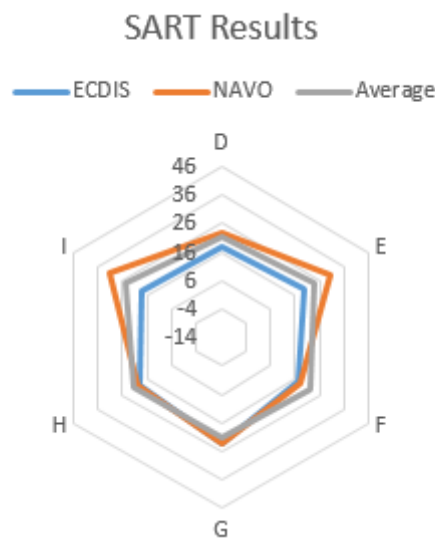


FIGURE 3.18: Figure with the results of the SART questionnaire

3.3.2.7 Individual and team workload

It should be recalled that in the Expanded NASA-TLX questionnaire, the values for individual Workload come from a formula based on the answers on a Likert Scale, ranging from Very Low (1) to Very High (20). This composite result can range from 5 to 100. The formula used is presented in Chapter 2.

A higher value represents a higher level of Workload, which in turn is suggested by literature to be a precursor to worse performance. When it comes to team workload, each answer should be interpreted separately and the ones chosen for analysis were team efficacy, team support and team dissatisfaction.

The values are directly based on the answers on a Likert Scale, ranging from Very Low (1) to Very High (20). There couldn't be found any literature relating each answer to team workload questions to performance. Yet, higher levels of team

support and team effectiveness are generally correlated with better performances, and higher levels of team dissatisfaction with worse performances (Kim et al., 2020).

The average results didn't show a high level of variability, but teams F and G recorded the highest values. The same didn't happen for ECDIS operators, whose variability was significantly higher, with teams G and I registering the top composite results. Among NAVOs, with higher variability as well, team H and I registered the highest values of individual Workload.

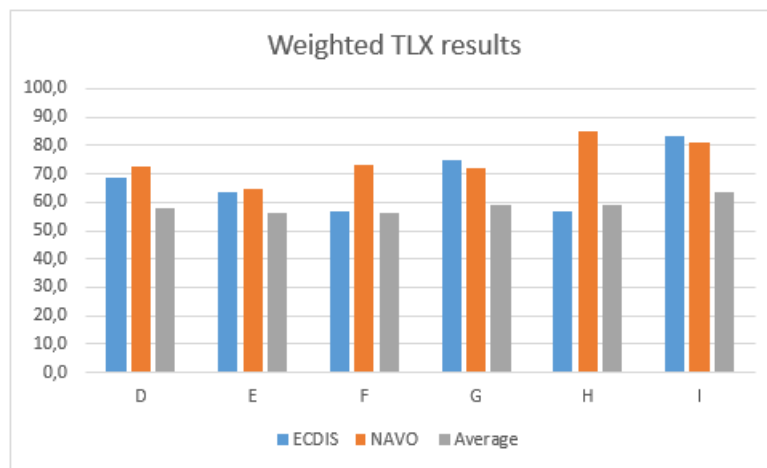


FIGURE 3.19: Weighted NASA-TLX results

As for the cooperative parameters, in the average of all team members, team F recorded the highest value for team supportiveness (question 11) while recording the lower value for team dissatisfaction (question 12). The most interesting variation was recorded on the answers for question 12, with teams G and I registering more than the double of dissatisfaction from teams E and F.

Team	Weighted TLX	Team efficacy	Team support	Team dissatisfaction
Average D	61,7	10,4	14,2	6,2
Average E	61,6	10,4	15,7	4,7
Average F	66,1	10,4	16,8	4,6
Average G	63,9	10,5	16,8	9,9
Average H	62,3	10,5	16,3	8,4
Average I	60,1	16,3	15,8	10,3

TABLE 3.20: Average results for the Expanded NASA-TLX questionnaire

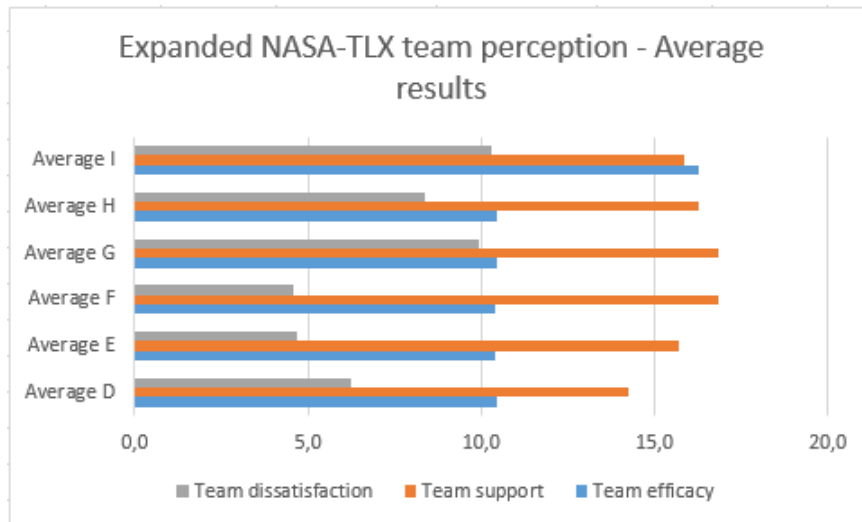


FIGURE 3.20: Average results in team perception for the Expanded NASA-TLX questionnaire

When it comes to the ECDIS operator, teams E and I registered the highest values for team supportiveness. Yet, team I also registered the higher value of team dissatisfaction, almost double the amount of the second-highest value from team F.

Team	Function	Weighted TLX	Team efficacy	Team support	Team dissatisfaction
D	ECDIS	68,7	5,0	9	9
E	ECDIS	63,7	20,0	19	2
F	ECDIS	56,7	5,0	8	10
G	ECDIS	75,0	14,0	14	8
H	ECDIS	56,7	17,0	17	2
I	ECDIS	83,3	17,0	20	19

TABLE 3.21: ECDIS operators' results for the Expanded NASA-TLX questionnaire

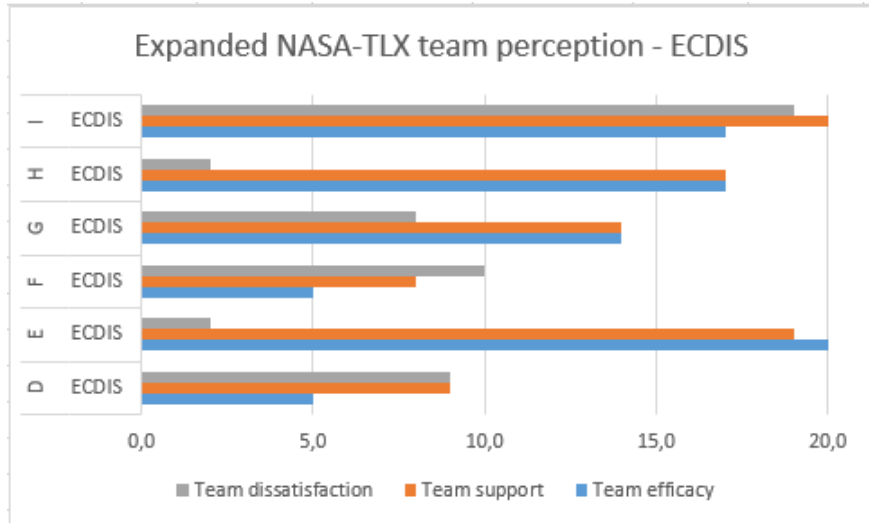


FIGURE 3.21: ECDIS operators' results in team perception for the Expanded NASA-TLX questionnaire

Regarding the NAVO, team H and I recorded the higher values for team supportiveness while registering the lower values for team dissatisfaction.

Team	Function	Weighted TLX	Team efficacy	Team support	Team dissatisfaction
D	NAVO	72,3	17,0	13	7
E	NAVO	64,7	15,0	15	5
F	NAVO	73,3	2,0	12	16
G	NAVO	72,0	12,0	14	16
H	NAVO	85,0	19,0	19	3
I	NAVO	81,0	17,0	16	2

TABLE 3.22: NAVO's results for the Expanded NASA-TLX questionnaire

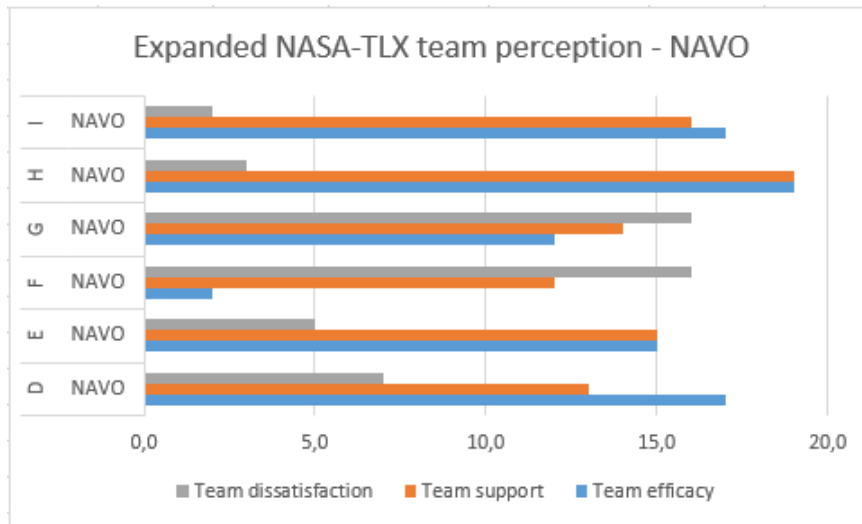


FIGURE 3.22: NAVO’s results in team perception for the Expanded NASA-TLX questionnaire

3.3.3 Procedure Compliance

3.3.3.1 Piloting procedures

Due to the PTC evaluators’ unavailability to perform the piloting procedure compliance assessment, this was only measured in two experiments, with team F and team G.

It should be recalled that reports used by the evaluators in each session, account for two main indicators. The first is global evaluation, a subjective performance result ranging from Below Standard to Very Good. The second is the number of aspects to improve (AtI), which can be critical, significant, and minor. The goal is to have the least AtI’s possible.

Between the two, Team G registered the best global evaluation, with the grade "Marginally satisfactory", while team F was awarded the grade "Below Standard". As for the number of Aspects to Improve (AtI’s), team F recorded the higher amount of critical and significant AtI, although recording the lower amount of minor AtI.

CITAN Report		
Parameter	Team F	Team G
Global Evaluation	Below Standard	Marginally Satisfactory
Critical AtI's	3	1
Significant AtI's	8	5
Minor AtI's	1	6

TABLE 3.23: Results of the PTC reports

3.3.3.2 Post-disruption procedures

The post-disruption procedure checklist is divided into two categories. The first is Detection and communication (E.g., assessing if both spoofing and jamming were detected and communicated). The second is Impact Acknowledgment (E.g., assessing the acknowledgment of the impact of the disruptions on RADAR ARPA, AIS, and if the positioning source was changed on ECDIS). The goal is to comply with as many checklist items as possible.

Team H and I recorded the higher values in both categories: Detection and reporting; Impact Acknowledgment. Therefore, globally, they also recorded the total number of post-disruption actions performed, with teams D and F on the lower end of the spectrum.

	Post-disruption actions		
	Detection and reporting	Impact Acknowledgment	Global
D	2	1	3
E	4	1	5
F	3	1	4
G	6	1	7
H	8	2	10
I	6	4	10

TABLE 3.24: Table with number of post-disruption actions performed

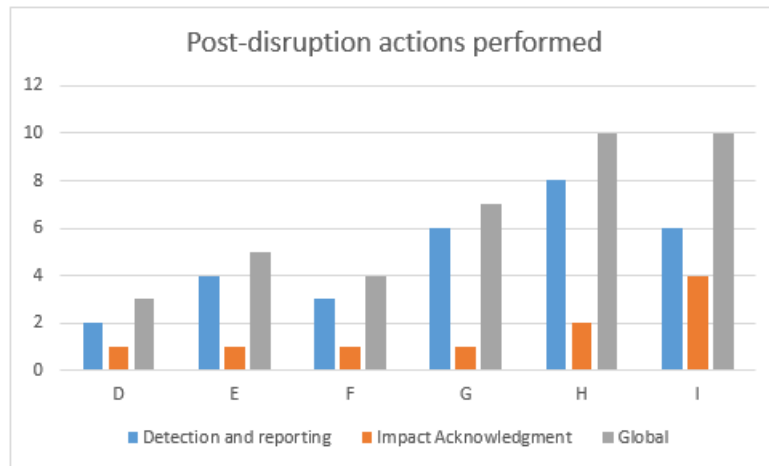


FIGURE 3.23: Chart with number of post-disruption actions performed

Chapter 4

Discussion

4.1 Piloting model building

4.1.1 Work as Prescribed vs. Work as Done

Although the prescribed procedure for piloting in the Portuguese navy incorporates satellite navigation through GNSS information in the GPS receptor, ECDIS, AIS, and ARPA, it is designed to be independent of it (Estado-Maior da Armada, 2008). Therefore, the only real identifiable bottleneck, meaning the only procedure (and so the only FRAM function) that cannot be executed without these systems, is the prescribed positioning accuracy of 10 m, which cannot always be assured through the use of visual fixes.

For all other functions, although some can be executed through GPS information, there are alternatives to its use on the bridge. On the other hand, in a GNSS disruption situation, some preparations assume a higher level of importance. This is the case of the definition of visual and RADAR aids. Some functions also lose their backup, for example, the registry of the impact of wind and the drift or providing collision avoidance information.

On the other hand, when performing the qualitative analysis of the teams in the study executing piloting while facing a GNSS disruption, several differences were identified between the work as prescribed and work as done. This was especially the case when it came to using the full potential of the bridge equipments, namely the ECDIS. These findings are in line with what is suggested by literature regarding the impact of GNSS disruptions on teams and equipment usage (Grant et al., 2009).

Starting with the reaction to spoofing, although three teams detected it and reported it immediately, one team couldn't identify the disruption, reporting on the false position throughout the leg. On the other hand, two other teams reported on

the false position only in one report cycle, as the detection wasn't immediate. Still, they did end up detecting and reporting it within 3 minutes of the disruption.

In addition, when spoofing was detected, several alarms went off, some of them indicating possible sources and impacts of the problem, such as satellite reception errors and main positioning and heading source errors. Yet, every ECDIS operator in the study reported only the generic positioning error, not reporting on the alarms, with five operators also not troubleshooting based on this information.

Almost all teams detected the spoofing and stopped using or trusting the GPS information source displayed on ECDIS. Yet, several teams kept trusting other systems or functions also affected by the disruption, namely reporting the drift and AIS information (on ECDIS and RADAR).

Most of the teams, as prescribed, executed visual fixes on the ECDIS equipment from the beginning of the experiment. Yet, only two teams kept on doing so (even more often) after the disruption, with the remaining teams either slowing down the rhythm in which they did so or stopping its use entirely, or even abandoning the equipment to execute other tasks for the team.

This resulted in the fact that two teams were also delayed in their detection and reporting of jamming. An effective way of troubleshooting the errors and effectively identifying the spoofing and jamming actions would be to correlate the information between the ECDIS and the GPS receptors, which was only observed in one of the experiments.

Another effective way of continuing to use the potential of the ECDIS would be switching to an alternative GPS source (which wouldn't work in the study) and ultimately choosing the EP+Auto configuration, which would base the information displayed in the fixes. Still, this procedure wasn't executed by most of the participants, with only two teams doing so, which were also the only teams that kept on making complete report cycles, using the ECDIS information throughout the whole experiment.

In most teams, the number of single interactions (interactions outside the report cycle) raised, especially immediately after each disruption, with several other team members interacting with the ECDIS and sometimes stopping their tasks to help with the troubleshooting. This resulted in the delay of the report cycles.

In some teams, this happened due to the presumption that it was the operator's fault and not the system's. During the disruptions, some teams had issues with

4.1. Piloting model building

using RADAR (mainly regarding inadequate preparations before the experiment), which left the NAVO only with its own information when the chart couldn't register the position correctly. This lack of confirmation, in two cases, led to confusion about the visual information and distances to the route of over 200 yards.

In some teams, after the disruption, there was generalized mistrust of the bridge equipments information, namely the RADAR, and changes in the participants' emotional state were also observed, with an increase in the feelings of frustration or nervousness.

This analysis was rooted in the first two methodological principles of Cognitive Systems Engineering: identifying the gaps and describing the associated conditions. The following section will be rooted in the third methodological principle, proposing how such situations can be mitigated or prevented (Hollnagel and Woods, 2005) to effectively have all JCSs involved in piloting working at their full potential.

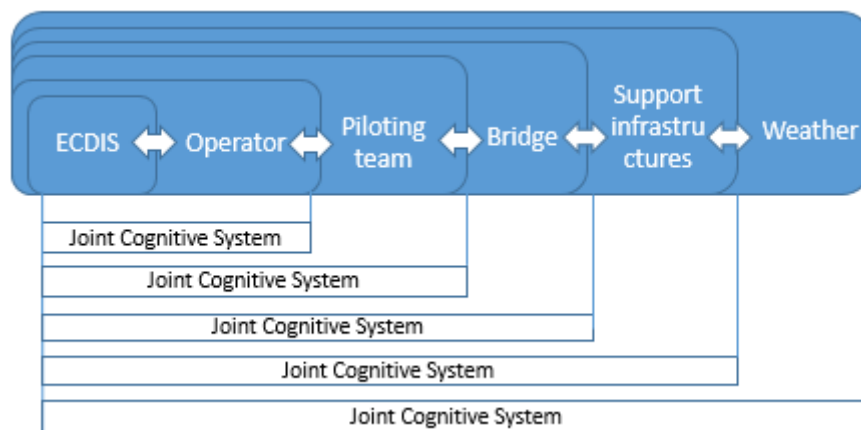


FIGURE 4.1: JCS's in the context of piloting

This is supported by including in the analysis the three threads of CSE, from how people cope with complexity and how they make use of artifacts, mentioned in this section, to how humans and artifacts can best effectively work together (Hollnagel and Woods, 2005), which will be explored in the following section.

The aforementioned differences also highlight the importance of performing the analysis of a piloting team through the scope of Joint Cognitive Systems because not only were technological and human factors differences found, but they were almost always intertwined. Although these differences between work as prescribed and work as done were identified, and some led to disturbances in procedure

compliance, team organization, and performance, the safety of navigation was never endangered. No situations of near collision or near grounding were observed.

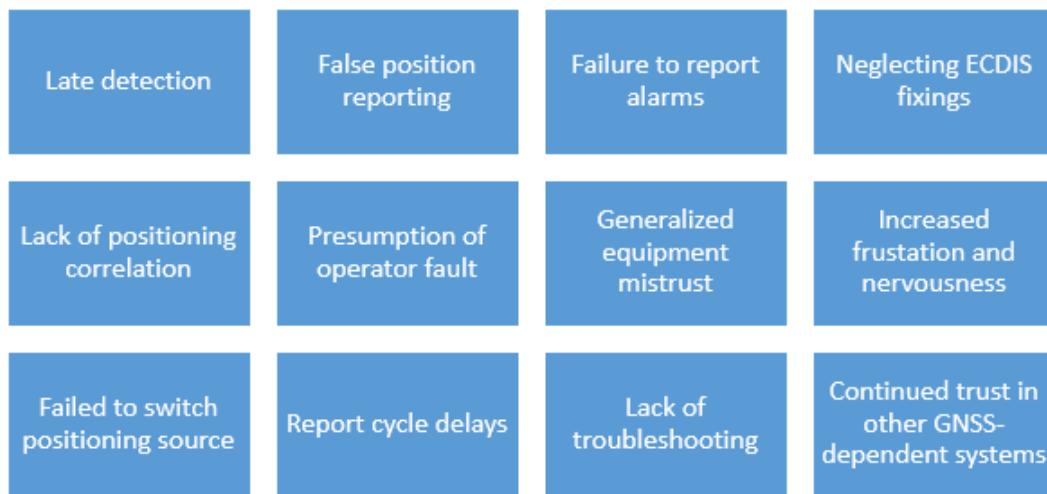


FIGURE 4.2: WAD vs. WAP Summary

4.1.2 Closing the gap

Chapter 2 mentioned the lack of pre-planned or prescribed responses to an eventual GPS jamming or spoofing on the bridge. There isn't any prescription written either in doctrine or in the ship's documentation (in the bridge cards, for example) (Trindade, 2018).

Therefore, teams are on their own, relying on their experience, expertise, and common sense to react to it without any overarching support instructions or theoretical background. So although one of the study's main conclusions is the need to address this issue to equip teams with better tools to manage the disruption during the event, Joint Cognitive Systems points to a more cyclical and further reaching view of engineering resilience (Hollnagel and Woods, 2005).

The resilience wheel mentioned in chapter 1 has four other stages besides the actual mitigation of the disruption. The focus is to stop the propagation and the cascade failures while keeping the core goals (Punzo et al., 2020).

In the after phase, it is expected that normal operations are resumed. Here we can again state that the institution doesn't provide guidelines for doing so. Yet, it is effectively a critical phase, as, for example, several tests must be carried out to ensure there is no longer a spoofing threat looming. Otherwise, if it is, it could be even more dangerous to assume the opposite.

As for the long after and long before phases, they mainly cover learning from the disruptions and readjusting and planning for future ones. These tasks could usually be carried out by a team or a department devoted to studying the issue, as is the case of the different work groups mentioned in chapter 1. Yet, in the Portuguese navy, there are no such groups. There is no structured and continuous data collection on GNSS signal or equipment failure and no formalized lessons learned document specific to these disruptions, as there is in the case of maritime accidents, for example.

Furthermore, a consistent study of the systems weaknesses and planning alert, response, and restoration procedures should be carried out, and, although there have been contributions in this area from other scientific work within the institution (Aresta, 2017), they haven't resulted in any actual implementation. Finally, the before phase is where monitoring the current state and, ideally, the disruption detection takes place.

Similarly to the during and after phases, there should also be guidelines regarding the expected actions if GPS jamming or spoofing is suspected. Yet again, there aren't. As mentioned in chapter 1, NATO is concerned with the subject of NAVWAR, considering it a real possibility in a war scenario and lack of preparation for it a liability (NATO, 2022). Indeed, the likelihood of a GNSS disruption shouldn't be treated as business as usual and instead have a set of actions to detect, mitigate, and restore normal operations.

It should be said that resilience is a concern in the design of all ships and equipments/systems. So in case of a GNSS disruption, alternative positioning sources can be used, and some even substitute for it automatically (Ioannides et al., 2016). Yet, this shouldn't be enough, as the resilience concern has to be extended towards knowledge, procedures, and people, and how they work and interact (Hollnagel and Woods, 2005). Only then can true resilience and preparedness be achieved.

As demonstrated in the present study, the resilience of the equipments and systems is not a sufficiently robust solution for the kind of readiness demanded by the scenarios and missions a modern navy must face.

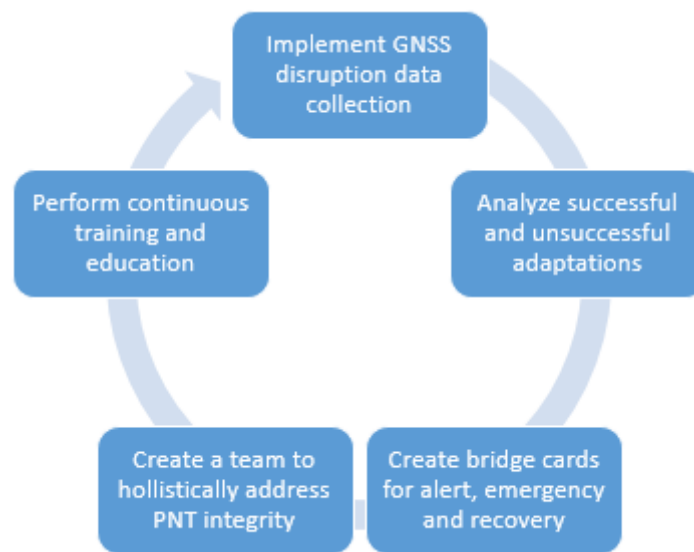


FIGURE 4.3: Implementation suggestions for the fleet

4.2 Pilot tests

4.2.1 Navigation

The performance results in the pilot tests showed a clear difference between the leg performed with normal availability of GNSS signal and the leg where the teams were undergoing the disruption. The teams registered an average difference between the legs of more than 100 yards, with one of them (team B) registering a 200-yard difference. The second leg couldn't be considered more demanding than the first one in terms of its characteristics. Therefore, this was likely caused by the reliance on the GPS information displayed on ECDIS.

Team A was the best performer and should therefore be considered a success case among the sample, being analyzed when looking for the success factors for resilient navigation. Although 200 yards off the route is a relatively high value (higher than the average of any participant teams in the experimental study), their positioning control remained steady during the disruption.

There aren't any previous studies concerning GNSS signal loss or denial in piloting, and none that measure positioning control. Therefore, the performance results obtained cannot be compared with the literature.

Section findings summary		
Pilot tests - Navigation		
Measurement	Expected result	Result
Average distance to route	Decay after disruption	Decay after disruption

TABLE 4.1: Pilot tests section findings summary - Navigation

4.2.2 Human factors

4.2.2.1 Trust in Automation

In terms of the average attitudes of the team towards the equipment they operated, the data does seem to present a compelling case for average higher levels of reliability, the propensity to trust and trust in automation being directly proportionate to the performance records, very much in accordance with the literature (Körber, 2018), as again the best performing team recorded the lowest values in all three parameters and the worst performing team recorded the higher values in all three as well.

As for the results of the ECDIS operator, they paint a similar picture, also in accordance with the literature, as the best performing team registering the lower values in all three parameters. Yet, the relationship weakens in the comparison between teams B and C, with the opposite being true, as the worst performer registered lower values in all three parameters.

Section findings summary			
Pilot tests - Trust in Automation			
Measurement	Expected result	Results	
		Team average	ECDIS
Reliability	Negative correlation	Negative correlation	No correlation
Propensity to Trust	Negative correlation	Negative correlation	No correlation
Trust in Automation	Negative correlation	Negative correlation	No correlation

TABLE 4.2: Pilot tests section findings summary - Trust in Automation

4.2.2.2 Interactions between team members

Regarding interaction changes, the data doesn't allow for comparison concerning whether a higher or lower number of report cycles can be considered a success factor. This happens because, for instance, although team B performed the higher number of complete sequences, they did so while reporting on the false GPS position, affecting their performance.

Regarding the comparison between team C and A, the best performer performed fewer report cycles, but there wasn't an expressive difference, and therefore the data collected becomes inconclusive. Yet, it does seem to suggest that teams that have a more permissible environment in terms of their members interacting with each other outside the report cycles have the potential to be better performers, as the number of single interactions is directly proportional to the performance of the teams.

As for the general difference in interaction quality and number between the normal and disruption situations, no general differences were found. Therefore, the disruption didn't seem to impact the interactions between the team members.

Previous studies also didn't correlate performance with interaction changes, either with technology or team members, so the analysis above can't be compared with previous literature and constitutes another original contribution of the study.

Section findings summary		
Pilot tests - Interactions		
Measurement	Expected result	Results
Report cycles performed	Unknown	No correlation
Total single interactions	Unknown	Positive correlation

TABLE 4.3: Pilot tests section findings summary - Interactions between team members

4.2.2.3 Situational Awareness

When it comes to Situational Awareness, although the difference between the average results is not great, there does seem to be a connection between average higher levels of Situational Awareness and performance. Higher levels of SA were found in team A, followed by team C and team B.

This hypothesis becomes more robust with the analysis of the NAVO results with the same relationship being found and with more expressive results (the SA difference between best and worst performers is 15). Yet, the results for the ECDIS contradict these premises as it follows the opposite logic, with the best performer recording the lowest value of SA.

This wasn't the result that was suggested by literature as a higher level of Situational Awareness is typically linked to higher performance levels (Endsley and Kiris, 1995). Although this seems to weaken the relationship between the two factors, these results could be explained by the possibility that the operator could

4.2. Pilot tests

be more aware of its lack of control and understanding of the situation, performing a more honest self-assessment that could be a success factor.

Section findings summary				
Pilot tests - Situational Awareness				
Measurement	Expected result	Results		
		Team average	ECDIS	NAVO
Situational Awareness	Positive correlation	Positive correlation	Negative correlation	Positive correlation

TABLE 4.4: Pilot tests section findings summary - Situational Awareness

4.2.2.4 Individual and team workload

As for individual workload, the weighted workload average results don't indicate any relationship between this factor and success, as all teams recorded very similar results. Yet, in accordance with the literature (Biondi et al., 2021), the results for the ECDIS operator and the NAVO seem to indicate that a lower workload level is connected to better performance, as team A recorded the lower values for both functions. Yet, the comparison again loses weight when analyzing the difference between team C and team B, where the opposite is true.

The results were somewhat confusing regarding team workload and did not indicate any link between performance and the self-assessment of team efficacy, support, and dissatisfaction.

Section findings summary				
Pilot tests - Individual and team workload				
Measurement	Expected result	Results		
		Team average	ECDIS	NAVO
Individual workload	Negative correlation	No correlation	No correlation	No correlation
Team efficacy	Unknown	No correlation	No correlation	No correlation
Team support	Unknown	No correlation	No correlation	No correlation
Team dissatisfaction	Unknown	No correlation	No correlation	No correlation

TABLE 4.5: Pilot tests section findings summary - Individual and team Workload

A summary of the measurements and findings of the pilot tests can be seen in the following figure.

Measurement	Expected	Result
Positioning Control	Decay after disruption	Decay after disruption
Trust in Automation	Negative correlation	Negative correlation (Team average)
Team interactions	No previous findings	Mixed results
Situational Awareness	Positive correlation	Positive correlation (Team average and NAVO)
Individual Workload	Negative correlation	No correlation
Team Workload	No previous findings	No correlation

FIGURE 4.4: Measurements and findings summary for the pilot tests

4.3 Experimental study

4.3.1 Navigation

Regarding the control of time performance measurement, there weren't any differences between the ETA-ATA difference to wheel over point in the wheel over points performed with normal availability of GNSS signal and the wheel over points performed while undergoing the disruptions. Therefore, with the data of the experimental study, it can't be said that GPS jamming or spoofing impacted the team's control of time. Besides, the ETA-ATA wheel over point difference didn't show considerable differences between the participating teams.

Only team F was the stand-out, demonstrating superior control with a result close to zero. Yet, this didn't hold up as the inverse happened in terms of ETA-ATA to the end difference, being several minutes late in comparison.

Although the difference was relatively short, team H and team I were the superior performers regarding time control, arriving only 3 and 2 minutes late, respectively. This superior performance was confirmed in positioning control. Team

H and I were the better performers in all three parameters measured, although sometimes followed closely by one team, different in each.

Besides, as mentioned in the previous chapter, the two teams were the only ones who performed above average in every parameter. Therefore, they were selected as the success cases, with the study pursuing the identification of the success factors within the different possibilities raised by the study's measurements.

Regarding positioning control throughout the experiments, the data shows strong evidence that, on average, the GNSS disruptions were directly related to a worse positioning control, sometimes by several hundred yards compared to the normal signal availability. Yet, the data also evidences that this is only the case for the worst performing teams, as three teams were able to attain an equal or even better positioning control, as was the case of teams H and I.

These claims were supported by the average and maximum distance to the route measurements in which compelling differences were found between the Normal and Spoofing and Jamming situations. Yet, the percentage of time on route measurement was somewhat inconclusive. The average result in all stages is very similar, and the data for each team does not record significant variation.

Surprisingly, most teams registered higher values while undergoing the disruptions. With this said, there aren't any previous studies concerning GNSS signal loss or denial in piloting that measure positioning and time control. Therefore, the performance results obtained cannot be compared with the literature.

Regarding detection time, almost all teams were within the 3-minute detection criteria for resilience both in spoofing and jamming detection. The exception is team E which took 9 minutes to identify the spoofing disruption. Therefore, it cannot be considered a resilient team even before the performance analysis as it failed the detection criteria. On the other hand, teams G, H, and I detected both disruptions immediately. Therefore, immediate detection of the disruption can be considered a success factor.

Finally, in terms of the different adaptations that the teams made while facing the disruption, they were mainly made at the level of the ECDIS operator. Considering that the two clear best performers made the same decisions in adapting the role of the ECDIS, which weren't followed by any other teams, it is likely that these are successful adaptations.

Therefore, the adaptation of the ECDIS operator on station and reporting based on the information from the visual fixes should be considered a success factor. In the following figure, it is possible to see the successful and unsuccessful adaptations to the disruption based on this analysis.

Team	On station	Reporting	Intentionally reported GPS	Reported fixings instead
D	No	No	No	No
E	No	No	No	No
F	Yes	No	No	No
G	Yes	Yes	Yes	No
H	Yes	Yes	No	Yes
I	Yes	Yes	No	Yes

TABLE 4.6: Successful and unsuccessful ECDIS adaptations

The following figure is a summary of the findings of the present section.

Section findings summary		
Experimental study - Navigation		
Measurement	Expected result	Result
ETA-ATA difference to wheel over point	No decay	No decay
ETA-ATA difference to the end	No decay	Unknown
Disruption detection time	Unknown	Generally acceptable
Successful adaptations	Unknown	Identified
Average distance to route	No decay	Decay after disruption
Maximum distance to route	No decay	Decay after disruption
Time on route	No decay	Decay after disruption

TABLE 4.7: Experimental study section findings summary - Navigation

4.3.2 Human factors

4.3.2.1 Time on team and Training

When it comes to the time on the team, from the two best performing teams, one is on the higher end of the specter while the other is on the lower one. Concerning the other teams, the assumption that teams with a higher average would be better performers also doesn't hold up. Although there isn't any literature on navigation relating to experience and performance, this contradicts more general studies which found a positive correlation between the two (Parasuraman and Riley, 1997).

Yet, the data shows convincing evidence that Training can be a decisive success factor, very much in line with what has been found in studies that relate Training with performance (Aragon et al., 2014). Both teams H and I, were the

4.3. Experimental study

teams that went through a full training plan more recently, with a powerful difference from all the other participants. Yet, the data isn't so clear to interpret when it comes to the number of similar exercises to the one performed in the study in 2022. This happens because the availability of the teams is very much dependent on their operational planning.

Yet, neither of the best performing teams is on the lower side of the specter in this parameter, with team I being the team that performed the highest number of these exercises. Yet, team D, the runner-up, didn't perform so well; therefore, the number of SIMPILOTExs performed in 2022 doesn't seem to be a success factor.

Section findings summary		
Experimental study - Time on team and Training		
Measurement	Expected result	Result
Time on Team	Unknown	No correlation
Recently undergoing a full training plan	Positive correlation	Positive correlation
Number of SIMPILOTExs	Positive correlation	No correlation

TABLE 4.8: Experimental study section findings summary - Time on team and Training

4.3.2.2 GNSS Knowledge

One of the main reasons specific knowledge of the impact of a GNSS outage or tampering on the bridge equipments was raised as a possible success factor was that teams would continue to rely on the information from AIS, both on ECDIS and RADAR. Yet, all teams, both NAVOs and ECDIS operators as well as on average, were able to identify that these two equipments worked with GNSS information successfully.

So the problem of trusting the information didn't hold up as a matter of lack of theoretical knowledge but remains to be explained. It is possible that the focus of the team's and its members on the task and the positioning error doesn't allow them to access this knowledge, or habit might also play a role in overriding their knowledge with what they usually do.

Yet, the best performing teams did register the highest number of correct answers for the questionnaire. This happened for NAVOs, ECDIS operators, as well as on average. Yet, the difference was minimal; therefore, given the sample, it cannot be considered a success factor.

This constitutes an original contribution to the study, as this hasn't been tested in previous literature. Possibly, some team members that didn't specifically

acknowledge the impact on AIS or RADAR didn't do so, not because they weren't aware of it from a theoretical perspective. Perhaps their focus on the task and unfamiliarity with the situation led them to fail to use that knowledge at the time.

Section findings summary				
Experimental study - GNSS Knowledge				
Measurement	Expected result	Results		
		Team average	ECDIS	NAVO
Total correct answers	Unknown	No correlation	No correlation	No correlation
Identifying AIS and ARPA	Unknown	No correlation	No correlation	No correlation

TABLE 4.9: Experimental study section findings summary - GNSS knowledge

4.3.2.3 Trust in Automation

While the pilot tests provided interesting evidences that lower values of reliability, the propensity to trust, and trust in automation could be linked to better performance, this wasn't true for the experimental study. For ECDIS operators, the trust in automation parameter was similar across the board, with relatively high values of 4 and 4.5.

The best performing teams didn't register lower values of propensity to trust and fell somewhat in the middle of the table in both parameters. This contradicts previous findings, which suggest a negative correlation between trust in automation and performance. Therefore, the data suggests that trust between the ECDIS operator and equipment is not a success factor for more resilient navigation.

Section findings summary		
Experimental study - Trust in Automation		
Measurement	Expected result	Result
Reliability	Negative correlation	No correlation
Propensity to Trust	Negative correlation	No correlation
Trust in Automation	Negative correlation	No correlation

TABLE 4.10: Experimental study section findings summary - Trust in Automation

4.3.2.4 Interactions between team members

The pilot tests raised the possibility that teams that felt more at ease having interactions between the team members outside the report cycle could be better performers. Yet, in the experimental study, this possibility wasn't confirmed.

In fact, the data doesn't really lean in one direction, with the single interactions of the NAVO and the ECDIS operators' results being extremely varied among the different participants. The report cycle's per minute measurement registered similar results in all teams and, therefore, can't be considered a success factor.

Yet, contrary to the pilot tests, the total number of single interactions per minute on the bridge data does seem to indicate that the high-performing teams had fewer interactions outside the report cycle. They also registered a lower variation of single interactions between the normal and spoofing or jamming situations.

Therefore, a less interactive bridge and more procedural-focused, although allowing some level of single interactions, seems to be a success factor for more resilient navigation. Similarly to the pilot tests, there weren't any expressive differences between the number of single interactions or report cycles per minute between the normal and spoofing or jamming situations.

Section findings summary				
Experimental study - Interactions between team members				
Measurement	Expected result	Results		
		Team average	ECDIS	NAVO
Report cycles /min	Unknown	No correlation	Non applicable	Non applicable
Single interactions/min	Unknown	Negative correlation	No correlation	No correlation

TABLE 4.11: Experimental study section findings summary - Interaction between team members

4.3.2.5 Interactions with technology

Contrary to the interaction between team members, there were robust differences between the number of interactions per minute with the ECDIS equipment in normal navigation and undergoing the GNSS disruptions. A much higher number of interactions in the normal situation progressively declined throughout the experiment.

This could be explained by the fact that the ECDIS operator would frequently give up interacting with the equipment or leave it entirely, as mentioned in the FRAM analysis. Besides, the teams that were able to sustain or even increase their level of interaction with ECDIS were precisely the best performing teams, H and I. This happened for the use of fixes (which allowed the ECDIS to remain in the report cycle) and the total number of interactions (with many of them associated with troubleshooting).

Therefore, there is strong evidence that a higher interaction level with ECDIS is a success factor for more resilient navigation. It should be recalled that previous studies also didn't correlate performance with interaction changes, either with technology or with team members, so the above analysis can't be compared with previous literature and constitutes an original contribution to the study.

Section findings summary		
Experimental study - Interactions with technology		
Measurement	Expected result	Result
Number of visual fixes/min	Unknown	Positive correlation
Total number of interactions/min	Unknown	Positive correlation

TABLE 4.12: Experimental study section findings summary - Interaction with technology

4.3.2.6 Situational Awareness

The SART results were very similar for the ECDIS operators and NAVOs, as well as on average. This means there weren't any data points that really stood out, so the analysis is fundamentally inconclusive. Team I, one of the best performing teams, registered higher values of Situational Awareness in the NAVO and on average. Yet, they recorded one of the lower values for the ECDIS operators'. And then, Team H, the other best performing team, registered the lower values of SA on the two functions chosen for analysis and on average.

With inconsistent results, Situational Awareness can't be considered a success factor for more resilient navigation. This wasn't the result that was suggested by literature as a higher level of Situational Awareness is typically linked to higher performance levels (Endsley and Kiris, 1995).

Section findings summary				
Experimental study - Situational Awareness				
Measurement	Expected result	Results		
		Team average	ECDIS	NAVO
Situational Awareness	Positive correlation	No correlation	No correlation	No correlation

TABLE 4.13: Experimental study section findings summary - Situational Awareness

4.3.2.7 Individual and team workload

The Expanded NASA-TLX questionnaire didn't reveal any particularly interesting tendency. On average, they were very similar among the different participating teams. The same is true for the ECDIS operators'.

A somewhat unexpected result was that the best performing team was on the higher specter of team dissatisfaction. This could be a result of the fact that a team that went through a full training is more demanding about its own performance, being more dissatisfied, although it has achieved a comparably higher performance level. Yet, there were not so well-performing teams in the same circumstance. Therefore, it can't be considered a success factor.

Regarding the NAVO, the two best-performing teams recorded higher values of individual workload, with a considerable difference. This contradicts the literature, as it would be expectable for them to have a lower workload as they dealt more easily with the situation (Biondi et al., 2021). Yet, it could indicate that they performed a higher effort than the other participants, achieving higher results despite the higher workload.

Perhaps a better explanation could be that upon a GNSS disruption, these NAVOs decide to double down on their own information, increasingly focusing on the rigor and effectiveness of their own work (resulting in a higher workload). It appears to be a success factor, although it should be looked at with skepticism.

As for the NAVO's results in team perception, the best performing teams had higher values of team efficacy and support and lower values of team dissatisfaction. This means a positive team perception by the NAVO does seem to be a success factor for more resilient navigation, even more so as the NAVO has the role of being the team leader.

Section findings summary				
Experimental study - Individual and team workload				
Measurement	Expected result	Results		
		Team average	ECDIS	NAVO
Individual workload	Negative correlation	No correlation	No correlation	Positive correlation
Team efficacy	Unknown	No correlation	No correlation	Positive correlation
Team support	Unknown	No correlation	No correlation	Positive correlation
Team dissatisfaction	Unknown	No correlation	No correlation	Negative correlation

TABLE 4.14: Experimental study section findings summary - Individual and team Workload

4.3.3 Procedure Compliance

4.3.3.1 Piloting procedures

Although the data was limited for the reasons mentioned in the previous chapter, the data collected points to a strong influence of piloting procedure compliance on team performance.

The team with the best global evaluation and the lower number of critical and significant AtI's was largely the best performing team, both in time and positioning control. Although it had a higher number of minor AtI's it probably only did so because its superior performance left more room for more minor improvements, instead of critical or significant ones. Therefore, the comparison is strong evidence that piloting procedures compliance is, in fact, a resilient navigation success factor.

Although there is no literature effectively assessing the relationship between procedure compliance and performance in the maritime domain, all training and evaluation are based upon the principle that procedure compliance is a cornerstone of superior performance, and the results are precisely in accordance with that assumption.

Section findings summary		
Experimental study - Piloting procedure compliance		
Measurement	Expected result	Result
Global evaluation	Positive correlation	Positive correlation
Number of critical AtI's	Negative correlation	Negative correlation
Number of significant AtI's	Negative correlation	Negative correlation
Number of minor AtI's	Negative correlation	Positive correlation

TABLE 4.15: Experimental study section findings summary - Piloting procedure compliance

4.3.3.2 Post-disruption procedures

The same was found to be true for executing the recommended post-disruption actions. As the checklist elaborated for the study was not previously available to the teams beforehand, the teams with higher compliance did so somewhat instinctively.

They did this by following what can be called common sense best practices, as they are not written in navy doctrine or the ships' bridge cards. Yet, the teams that registered higher compliance were the best-performing ones, with a considerable difference from all the other teams.

4.3. Experimental study

Therefore, the data collected presents powerful evidences that more direct and correct actions in the face of a GNSS disruption in maritime navigation are a successful factor for managing it. It also provides compelling evidence that the checklist built in collaboration with the PTC specialists is an effective set of actions to respond to either jamming or spoofing.

Both procedure compliance measurements are original contributions of the study and therefore can't be compared with previous findings. Yet, the results align with the common assumption that higher levels of procedure compliance result in higher performance levels.

Section findings summary		
Experimental study - Post-disruption procedure compliance		
Measurement	Expected result	Result
Number of post-disruption actions performed	Unknown	Positive correlation

TABLE 4.16: Experimental study section findings summary - Post-disruption procedure compliance

A summary of the measurements and findings of the experimental study can be seen in the following figures. The first summary consists of the same measurements as the pilot tests and includes a comparison with the latter's findings. The second summary contains all the remaining measurements used only in the experimental study.

Measurement	Expected	Pilot tests	Result
Positioning Control	No changes	Decay after disruption	Decay after disruption
Trust in Automation	Negative correlation	Negative correlation (Team average)	No correlation
Team interactions	No previous findings	Mixed results	Mixed results
Situational Awareness	Positive correlation	Positive correlation (Team average and NAVO)	No correlation
Individual Workload	Negative correlation	No correlation	No correlation (Except for NAVO)
Team Workload	No previous findings	No correlation	No correlation (Except for NAVO)

FIGURE 4.5: Measurements and findings summary for the experimental study and pilot tests comparison

Measurement	Expected	Result
Technology interaction	No previous findings	Positive correlation
Time Control	No changes	No changes
Time on Team	No previous findings	No correlation
Training	Positive correlation	Positive correlation (for training plan)
GNSS Knowledge	Positive correlation	No correlation
Procedure Compliance (Piloting and post-disruption)	Positive correlation for both	Positive correlation for both

FIGURE 4.6: Experimental study's remaining measurements and findings summary

Conclusion

The present study was motivated by the growing dependency on radio satellite positioning systems such as GPS and the resilience concerns surrounding both that dependency and the proven fragilities of such systems. Requirements for position, navigation, and timing (PNT) sources are increasing, and the quality and integrity of those three factors have become decisive elements for success in maritime operations, especially navigation.

This has been pushing different stakeholders to search for resilience and its success factors. For its nature and the missions and scenarios faced, the Portuguese navy should be a part of this global effort, and this study intended to contribute to that. The proposed solution addressed the issue of PNT resilience through the scope of Joint Cognitive Systems, measuring teams' performance, procedure compliance, and human factors.

The latter meant measuring interactions with technology and other team members, trust in automation, situational awareness, and workload when faced with a GNSS disruption. As an experimental study and somewhat of a pioneering one, the scope was broad, as one of the main concerns was not to leave out any factor that could impact resilience, which would consequently be discarded in more narrow, focused studies.

Throughout the experiment, teams sequentially navigated with normal availability of GNSS signal, undergoing spoofing and jamming. The performance was measured through quantitative measurements of time and positioning control, and procedure compliance was assessed with the support of evaluators from the PTC. The human factors were primarily measured using questionnaires. The FRAM methodology (Functional Resonance Analysis Method) supported studying the differences between Work as Done and Work as Prescribed.

The study intended to provide extensive insight into the piloting teams' ability to navigate in the face of adversity and effectively upraise the knowledge on the resilience of the PNT function in the Portuguese navy to pave the way to technological and human solutions for better, more resilient navigation.

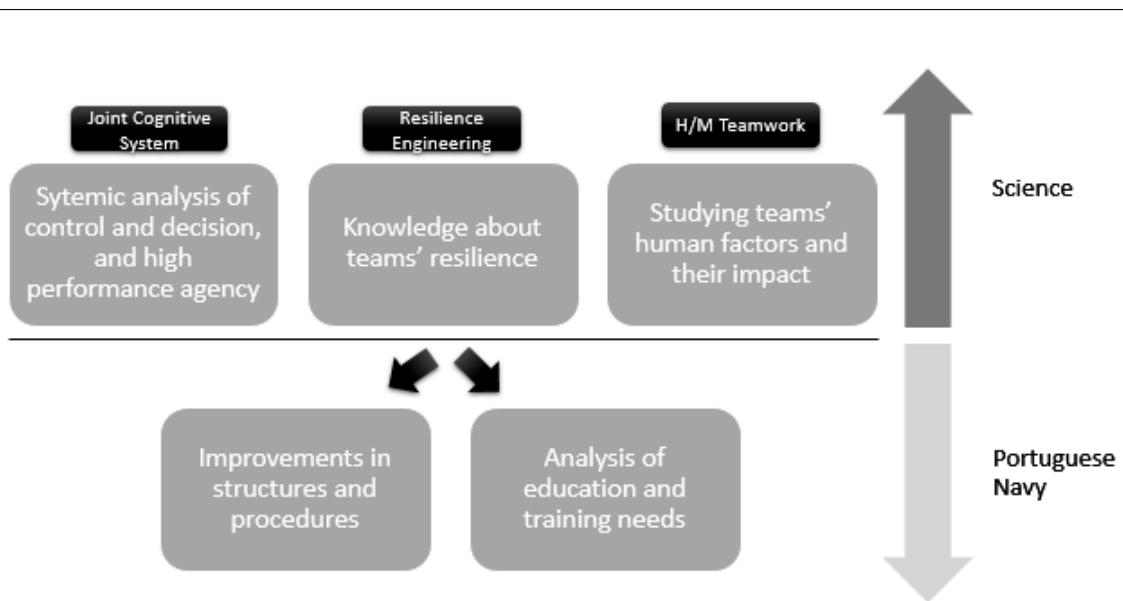


FIGURE 4.7: Contributions of the study

Further contributions to science were made with the participation in the 7th Hydrographic Engineering Conference organized by Instituto Hidrográfico. Another full article was submitted to the International Naval Engineering Conference (INEC) 2022 after passing the previous selection stages. It is currently awaiting revision.

The analysis of the Work as Done and Work as Prescribed revealed that although theoretically the prescribed model is robust and designed to work independently of GNSS signal, several deviancies were observed in the study. Although safety was never endangered, as there weren't any collision or grounding situations, several teams lacked spoofing detection.

After the disruption, they also reported false information, ignored alarms, and continued to trust GNSS-dependent systems. Some demonstrated a lack of use of visual fixes on ECDIS, stopping its use or abandoning the equipment entirely and not changing its configuration and setups or troubleshooting the positioning error. Changes in participants' emotional state and disruption of the report cycles were also observed, as well as a general mistrust of electronic equipment data.

Planning for these disruptions and specific procedural guidelines or checklists were also found lacking within the institution, failing to address all phases of the resilience wheel: long before the disruption, before, during, after, and long after, as there aren't any working groups, instructions in doctrine or bridge cards or organized data collection schemes in place.

GNSS spoofing and jamming were found to impact performance and human factors, namely behavior, with teams on average registering a slight increase in

distance to the route but with some teams registering a significant difference of more than 100 yards.

The impact on behavior, on average, seemed to be only identifiable in terms of the general increase of single interactions per minute, but several also registered differences in the report cycles and the single interactions of NAVO and the ECDIS operators’.

In terms of the success factors for more resilient navigation, the study points towards the success factors described in the following figure.

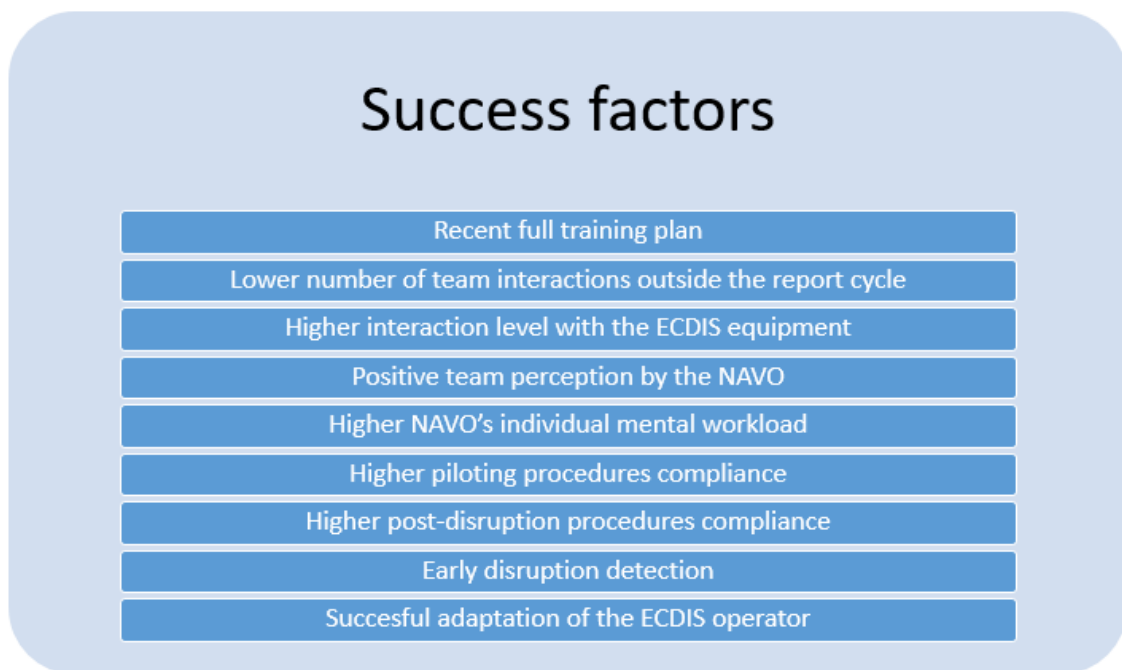


FIGURE 4.8: Success factors identified in the study

There were several obstacles to the execution of the plan for the experimental study, namely in terms of hardware and software availability (the fact that the ECDIS wasn't integrated with the rest of the bridge demanded the use of alternative hardware and software solutions).

The same happened in terms of human resources, as a total of 6 participant teams were able to perform the experiment in the available time (which had to be extended for over two months), falling short of the ambition of studying 12 teams and therefore having more than 100 participants in the study.

Yet, the study group was always able to find alternatives and ended up with a considerable amount of data collected, as mentioned in chapter 2.

The use of the PTC infrastructures and human and material resources was essential to the study, both on a technological perspective with the direct support of SES (Serviço de Engenharia de Sistemas), and on an organizational one in close cooperation with the GNFM (Gabinete de Formação de Navegação e Manobra) and the DTA (Departamento de Treino e Avaliação) whose members were also of precious help as navigation experts.

Besides the contribution above to science and the Portuguese navy, while working around these limitations, the present study also suggested a successful post-disruption actions checklist. A joint hardware-software solution was also developed, involving coding, that equipped the PTC with the fully operational capability of simulating GNSS disruptions in the ECDIS equipment, which it didn't have.

Future Work

Taking into account the extensive work in terms of protocol preparation and development, with the help of the 4-page checklist developed, future work can focus on collecting more data. It can do so with a broader time frame, focusing on each class or type of ship and doing so only with complete piloting teams, without the personnel limitations that the present study had to adjust to.

Then it can move in the direction of studying not only each factor in more depth but also some specific correlation between the different factors and not only their comparison with the performance levels to determine whether they're a success factor for resilient navigation.

The broader theme of GPS jamming and spoofing, as well as electronic and navigation warfare, should also be further explored. Studying, for example, the impact of GNSS signal loss or tampering in other maritime operations would contribute to the Portuguese navy's knowledge of these issues and result in higher readiness.

Specific actions which were not particularly addressed in the present study also deserve a more in-depth analysis. This is the case of the impact different briefing styles with different information can have on performance. Similarly, the delivery of an effective debriefing could be studied regarding its impact on learning and improvement.

The technological solution developed also allows different types of spoofing and jamming actions to be simulated. Therefore, it is now possible to study the

teams' ability to detect a spoofing disruption closest to the true position, for example (a 600-yard difference was used in the study, which is a considerable difference). Developing and testing a specific spoofing and jamming training program is also worth studying.

The FRAM model developed can also serve as a basis for future work in an in-depth risk assessment and analysis of a GNSS disruption in piloting.

Future work can also focus on the elaboration of checklists and guidelines for alert, emergency, and restoration for GNSS disruption situations which could be tested and provide a body of practical knowledge not only for the Portuguese navy but also for allied navies.

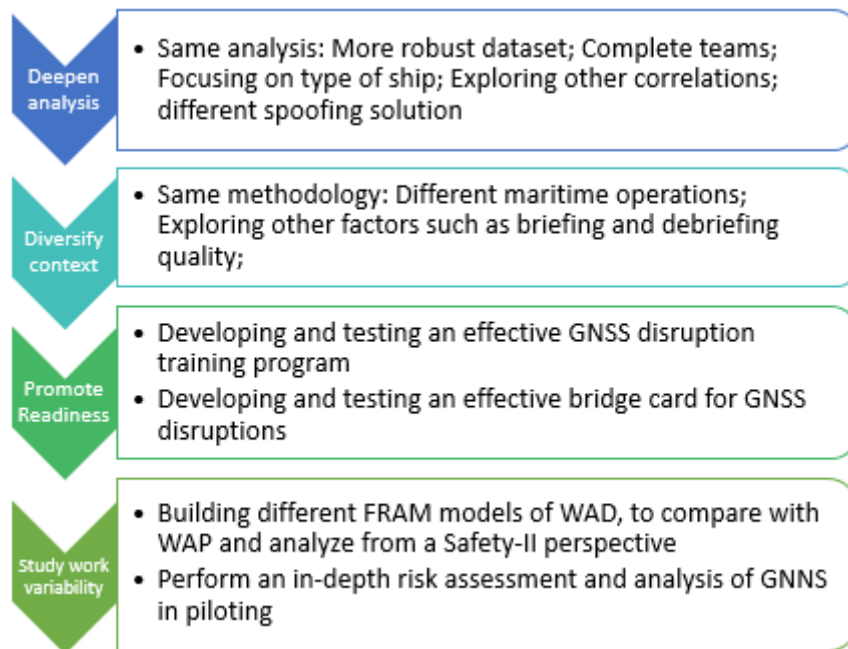


FIGURE 4.9: Future work summary

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Annex I - Study information leaflet



EN - CINA

Estudo experimental sobre a resiliência da navegação



Folheto informativo

A resiliência, que pode ser definida como a capacidade de superar ou recuperar de adversidades, na última década, tem sido um tema sobre o qual muito se tem falado e escrito, o que não é difícil de explicar tendo em conta que o mundo é cada vez mais volátil em virtude da velocidade a que tudo tem tendência a mudar. A indústria marítima não é exceção, com o aumento do tráfego marítimo e a integração de novas tecnologias a revelarem-se desafios que exigem hoje que uma navegação segura seja uma navegação resiliente. A importância deste tema é evidenciada pela produção crescente de artigos científicos sobre o tema, inclusive sendo um tema recorrente na *NATO Review*. Em paralelo têm também sido criadas diversas equipas de trabalho civis e militares, nacionais e internacionais, precisamente com o objetivo de encontrar soluções a diferentes níveis para a problemática da resiliência da navegação.

A Marinha Portuguesa, tendo em conta a importância da sua missão e das operações que leva a cabo, é naturalmente parte interessada em participar neste esforço global com vista a assegurar uma melhor e mais resiliente navegação. Considera-se então essencial que se aprofunde o conhecimento sobre as equipas de pilotagem, a forma como estas conduzem a navegação, como lidam com a adversidade e como é que os fatores humanos podem estar relacionados com a performance, ou seja, com a segurança da navegação. Este trabalho pretende então contribuir para a obtenção desse conhecimento através do estudo da entrada no Porto de Lisboa de diferentes equipas de pilotagem da Marinha Portuguesa, principalmente com recurso a gravações áudio e vídeo das séries, assim como com o preenchimento de alguns questionários para aferir a influência dos processos humanos.

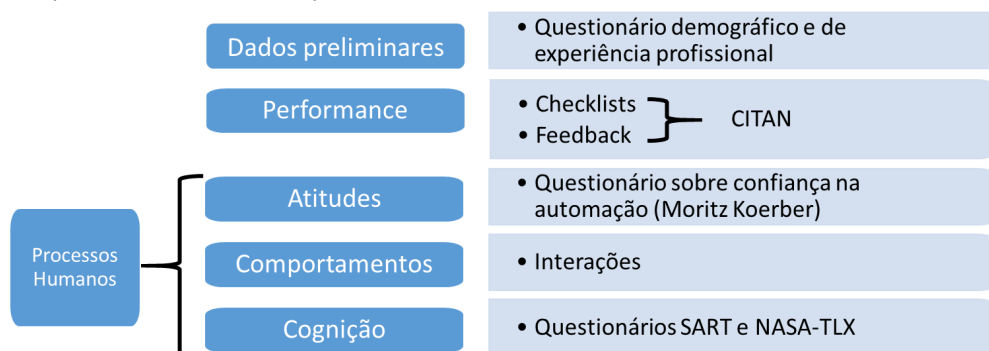


Figura 1- Esquema de recolha de dados

Adicionalmente será também pedido às equipas que preencham um questionário sobre memória transitiva (conhecimento que cada indivíduo possui em cada momento), nas dimensões especialização, credibilidade e coordenação. Pretende-se estudar a relação entre o desempenho e eficácia das equipas quer com a memória transitiva, quer com os tipos de vínculos existentes entre os elementos da equipa treinada.

Annex II - Demographic and Professional Background questionnaire

Questionário demográfico

1. Sexo: Masculino Feminino
2. Idade: _____
3. Posto e Classe: _____
4. Ano de entrada na Marinha: _____
5. Tempo embarcado (anos): _____
6. Número de horas de navegação: _____
7. Tempo no navio (meses): _____
8. Tempo na presente equipa (meses): _____
9. Função na equipa: _____
10. Experiência profissional (em diferentes unidades) nas presentes funções: _____

11. Tempo nas presentes funções na equipa (meses): _____
12. Tempo em outras funções da equipa (meses): _____
13. Cursos de formação frequentados no âmbito das presentes funções:

14. Quanto tempo de treino específico teve para as presentes funções (dias)?

Obrigado pela sua colaboração!

Equipa (identificação codificada):

Annex III - GNSS-dependent equipments/systems

Equipamentos e sistemas GNSS-dependentes

Assinale com um círculo os equipamentos/sistemas que considera receberem e utilizarem informação GPS e outros GNSS's no seu normal funcionamento. Assinale com uma cruz os que considera não receberem e utilizarem essa informação. Caso não saiba, deixe em branco.

Exemplo:

Central horária	Anemômetro	Radiogoniómetro
-----------------	-----------------------	-----------------

RADAR ARPA	Sistemas inerciais (MINS/SINS)	INMARSAT-C
------------	--------------------------------	------------

Sonda	Transreceptor MF/HF	Transreceptor VHF DSC
-------	---------------------	-----------------------

NAVTEX	Receptor GPS	ECDIS
--------	--------------	-------

SART	AIS	EPIRB
------	-----	-------

Função:

Obrigado pela colaboração!

Annex IV - Trust in Automation questionnaire

Questionário "Trust in Automation"	Discordo totalmente	Discordo	Não concordo nem discordo	Concordo	Concordo Totalmente	Sem resposta
1. O sistema é capaz de interpretar situações corretamente	(1)	(2)	(3)	(4)	(5)	<input type="radio"/>
2. O estado do sistema é sempre claro para mim	(1)	(2)	(3)	(4)	(5)	<input type="radio"/>
3. Eu já conheço sistemas similares	(1)	(2)	(3)	(4)	(5)	<input type="radio"/>
4. Os criadores do sistema são fidedignos	(1)	(2)	(3)	(4)	(5)	<input type="radio"/>
5. Deve ter-se cuidado com sistemas automatizados com os quais não se está familiarizado	(1)	(2)	(3)	(4)	(5)	<input type="radio"/>
6. O sistema é confiável	(1)	(2)	(3)	(4)	(5)	<input type="radio"/>
7. O sistema reage imprevisivelmente	(1)	(2)	(3)	(4)	(5)	<input type="radio"/>
8. Os criadores do sistema levam a sério o meu bem-estar	(1)	(2)	(3)	(4)	(5)	<input type="radio"/>
9. Eu confio no sistema	(1)	(2)	(3)	(4)	(5)	<input type="radio"/>
10. Uma avaria no sistema é provável	(1)	(2)	(3)	(4)	(5)	<input type="radio"/>
11. Eu consigo compreender o porquê das coisas se passarem como passam	(1)	(2)	(3)	(4)	(5)	<input type="radio"/>
12. Eu prefiro confiar do que desconfiar de um sistema	(1)	(2)	(3)	(4)	(5)	<input type="radio"/>
13. O sistema é capaz de assegurar tarefas complicadas	(1)	(2)	(3)	(4)	(5)	<input type="radio"/>
14. Eu posso confiar no sistema	(1)	(2)	(3)	(4)	(5)	<input type="radio"/>
15. O sistema pode fazer erros esporádicos	(1)	(2)	(3)	(4)	(5)	<input type="radio"/>
16. É difícil identificar o que o sistema fará a seguir	(1)	(2)	(3)	(4)	(5)	<input type="radio"/>
17. Eu já usei sistemas similares	(1)	(2)	(3)	(4)	(5)	<input type="radio"/>
18. Geralmente falando, os sistemas automatizados funcionam bem	(1)	(2)	(3)	(4)	(5)	<input type="radio"/>
19. Estou confiante nas capacidades do sistema	(1)	(2)	(3)	(4)	(5)	<input type="radio"/>

Função: _____ **Equipa (identificação codificada):** _____

Annex V - SART questionnaire

Questionário SART

CO NAVO Vigia ECDIS
OQP Leme/Telégrafos BPSO Carta

Técnica de avaliação de conhecimento situacional (*Situational Awareness Rating Technique -SART*)

Escala: 1 – Baixo < 7 - Alto

1. **Instabilidade da situação**
Quão variável é a situação? A situação é altamente instável e provável que mude repentinamente (Alto) ou é bastante estável e sem alterações (Baixo)?

1.	2.	3.	4.	5.	6.	7.
----	----	----	----	----	----	----
2. **Complexidade da situação**
Quão complicada é a situação? É complexa com muitos componentes interligados (Alto) ou é simples e estável (Baixo)?

1.	2.	3.	4.	5.	6.	7.
----	----	----	----	----	----	----
3. **Variabilidade da situação**
Quantas variáveis estão a mudar durante a situação? Existe um grande número de fatores a variar (Alto) ou há muito pouca alteração de variáveis (Baixo)?

1.	2.	3.	4.	5.	6.	7.
----	----	----	----	----	----	----
4. **Entusiasmo**
Quão entusiasmado(a) está com a situação? Está alerta e pronto(a) para atividade (Alto) ou possui um baixo grau de alerta (Baixo)?

1.	2.	3.	4.	5.	6.	7.
----	----	----	----	----	----	----
5. **Concentração da atenção**
Quão concentrado está na situação? Encontra-se concentrado em muitos aspetos da situação (Alto) ou focado em apenas um (Baixo)?

1.	2.	3.	4.	5.	6.	7.
----	----	----	----	----	----	----
6. **Divisão da atenção**
Quão dividida se encontra a sua atenção? Encontra-se concentrado(a) em muitos aspetos da situação (Alto) ou focado em apenas um (Baixo)?

1.	2.	3.	4.	5.	6.	7.
----	----	----	----	----	----	----
7. **Capacidade mental restante**
Quanta capacidade mental tem restante durante a situação? Possui suficiente para prestar atenção a muitas variáveis (Alto) ou nenhuma restante (Baixo)?

1.	2.	3.	4.	5.	6.	7.
----	----	----	----	----	----	----
8. **Quantidade de informação**
Quanta informação adquiriu durante a situação? Recebeu e compreendeu uma grande quantidade de informações (Alto) ou muito poucas (Baixo)?

1.	2.	3.	4.	5.	6.	7.
----	----	----	----	----	----	----
9. **Qualidade da informação**
Quão boa é a informação que adquiriu durante a situação? O conhecimento comunicado é muito útil (Alto) ou é insuficiente (Baixo)?

1.	2.	3.	4.	5.	6.	7.
----	----	----	----	----	----	----
10. **Familiaridade com a situação**
Quão familiar é a situação? Possui uma grande quantidade de experiência relevante (Alto) ou é uma situação nova (Baixo)?

1.	2.	3.	4.	5.	6.	7.
----	----	----	----	----	----	----

Equipa (identificação codificada):

Annex VI - Expanded NASA TLX questionnaire

Questionário NASA-TLX (Versão expandida)

CO NAVO Vigia ECDIS
OQP Leme/Telégrafos BPSO Carta

Circule, em cada linha, o campo que considera mais importante para avaliação da carga de trabalho associada à sua tarefa

Esforço	/	Desempenho
Desempenho	/	Exigência temporal
Desempenho	/	Frustração
Exigência física	/	Desempenho
Esforço	/	Exigência física
Exigência mental	/	Exigência física
Exigência temporal	/	Frustração
Exigência física	/	Frustração
Exigência mental	/	Esforço
Exigência temporal	/	Esforço
Exigência física	/	Exigência temporal
Frustração	/	Exigência mental
Frustração	/	Esforço
Exigência temporal	/	Exigência mental
Desempenho	/	Exigência mental

Índice de carga da tarefa
(Expanded NASA Task load Index)

Escala: 1 Baixo < 20 Alto

1. **Exigência mental**

Quanta atividade mental e perceptual é necessária (ex.: pensando, decidindo, calculando, lembrando, olhando, procurando, etc)? A tarefa foi exigente ou fácil, complexa ou simples?

Baixo	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Alto

2. **Exigência física**

Quanta atividade física foi necessária?
A tarefa foi exigente ou fácil, viva ou lenta, árdua ou frouxa, laboriosa ou repoussante?

Baixo	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Alto

3. **Exigência temporal**

Quantas vezes se sentiu pressionado devido ao ritmo no qual as tarefas ou elementos da tarefa ocorreram?
O ritmo era rápido e frenético ou lento e vagaroso?

Baixo	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Alto

4. **Desempenho**

Quão bem-sucedido acha que foi em realizar os objetivos da tarefa definida? Quão satisfeito está com o seu desempenho no cumprimento desses objetivos?

Baixo	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Alto

5. **Esforço**

Quão arduamente teve que trabalhar (mentalmente e fisicamente) para atingir seu nível de desempenho?

Baixo	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Alto

6. **Frustração**

Quão inseguro(a), desanimado(a), irritado(a) e stressado(a) versus seguro(a), gratificado(a), satisfeito(a), relaxado(a) se sentiu durante a tarefa?

Baixo	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Alto

7. **Exigência de coordenação**

Quanta atividade de coordenação foi necessária (por exemplo, correção ou ajuste)?
A coordenação exigia trabalhar em equipa de forma alta ou baixa, muito ou pouco frequentemente?

Baixo	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Alto

8. Exigência de comunicação

Quanta atividade de comunicação foi necessária (por exemplo, discutir, negociar, enviar e receber mensagens)?
A comunicação exigida foi alta ou baixa, frequente ou pouco frequente, complexa ou simples?

Baixo	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Alto

9. Exigência de partilha do tempo

Quão difícil foi compartilhar e administrar o tempo entre tarefas (trabalho feito em equipa)? Foi difícil ou fácil gerir tarefas individuais e aquelas que requerem trabalho com outros membros da equipa?

Baixo	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Alto

10. Eficácia da equipa

Quão bem-sucedida acha que a equipa estava a ser no trabalho em equipa? Quão satisfeito está com os aspetos de desempenho relacionados com a equipa?

Baixo	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Alto

11. Apoio da equipa

Quão fácil ou difícil foi fornecer e receber apoio dos membros da equipa (fornecendo orientação, ajudando os membros da equipa, fornecendo instruções, etc.)? Foi fácil ou difícil apoiar e receber apoio ou orientação de outros membros da equipa?

Baixo	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Alto

12. Insatisfação com a equipa

Quão emocionalmente desgastante e irritante *versus* emocionalmente recompensador e satisfatório foi trabalhar em equipa?

Baixo	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Alto

Equipa (identificação codificada):

Annex VII - Post-disruption actions checklist

Post-disruption actions	
Category	Parameter
Detection and reporting	ECDIS spoofing detected?
Detection and reporting	ECDIS spoofing reported?
Detection and reporting	GPS spoofing detected?
Detection and reporting	GPS spoofing reported?
Detection and reporting	Corelated with ECDIS with GPS data?
Detection and reporting	ECDIS jamming detected?
Detection and reporting	ECDIS jamming reported?
Detection and reporting	GPS jamming detected?
Detection and reporting	GPS jamming reported?
Impact Acknowledgment	Acknowledged impact on RADAR ARPA
Impact Acknowledgment	Acknowledged impact on AIS info displayed on ECDIS
Impact Acknowledgment	Stopped using positioning info from GPS on ECDIS?
Impact Acknowledgment	Changed main positioning source on ECDIS to geonavigation?

FIGURE VII.1: Post-disruption actions checklist

Annex VIII - Experimental protocol checklist

PNT Resilience and the impact of satellite radio positioning disruptions on pilotage teams

Check list for NAVSIM sessions

Planning

Week before

- Fleet command authorization VPC
- Preliminary meeting with CITAN VPC
- Coordination meeting about data collection and common protocol VPC/ASPOF Castro
- Technological solution setup for jamming/spoofing ECDIS ability..... ASPOF Castro
- Confirm with CITAN study participant teams for following week.....ASPOF Castro
- Send study information to participants and send METEO/oceanographic conditionsASPOF Castro
- Request the filling of the demographic questionnaire and NAVPLAN.....ASPOF Castro
- If possible prepare exercise with NAVPLAN introduced in Naval Academy SIMNAVASPOF Castro

Day before

- Check if NAVO provided the NAVPLAN waypoints.....ASPOF Castro
- Check equipment's / material
 - GoPro 1.....ASPOF Castro
 - Battery check
 - Memory check
 - GoPro 2.....ASPOF Castro
 - Battery check
 - Memory check
 - GoPro 3.....ASPOF Castro
 - Battery check
 - Memory check
 - Backup GoPro 1ASPOF Castro
 - Battery check
 - Memory check
 - Backup GoPro 2ASPOF Castro
 - Battery check
 - Memory check
 - Backup GoPro 3ASPOF Castro
 - Battery check
 - Memory check
 - Dictaphone 1ASPOF Castro
 - Battery check
 - Memory check
 - Chronometer 1ASPOF Castro
 - Battery check
 - Function check
 - Chronometer 2ASPOF Castro
 - Battery check
 - Function check
- Check forms and questionnaires
 - 10 PensASPOF Castro
 - ChecklistASPOF Castro
 - FORMEX 101 Key events briefing roomASPOF Castro
 - FORMEX 101 Key events seriesASPOF Castro

- 3 generic FORMEX 101ASPOF Castro
- 1 instructor position record formsASPOF Castro
- Pen drive with briefingASPOF Castro
- PointerASPOF Castro
- 10 Study Information form sheetsASPOF Castro
- 10 Demographic data sheetsASPOF Castro
- 10 Consent formsASPOF Castro
- 10 NASA-TLX questionnairesASPOF Castro
- 10 SART questionnairesASPOF Castro
- 10 TiA questionnairesASPOF Castro
- 10 Transitive Memory questionnairesASPOF Castro
- 10 GNSS information-dependent systems questionnairesASPOF Castro
- Staple all questionnaires and forms as necessaryASPOF Castro
- Prepare clipboardASPOF Castro
- Prepare FolderASPOF Castro
- Prepare ArchiveASPOF Castro

Execution

Hour before

- Map NAVPLAN waypoints in instructor.....SIMNAV Operator
- Put display of ECDIS and RADAR on screens of control room and set-up rec.....ASPOF Castro
- Make sure distance/time ruler is readily availableASPOF Castro
- Turn on NMEA simulator, setup specs and test it.....ASPOF Castro
 - Output stream = 2000ASPOF Castro
 - Wind = 315° 8 kts, water = 15° 50mASPOF Castro
- Set-up video cameras (3).....ASPOF Castro
- Set-up dictaphoneASPOF Castro
- Set-up briefing room with presentation, pointer, archive and folderASPOF Castro
- Coordination with control room about position registryASPOF Castro
- Coordination with control room about the exercise and proceduresASPOF Castro
- Make sure that the adequate platform is selected in accordance with ship's class.....ASPOF Castro
- Coordination with control room about time and disruption syncASPOF Castro
- Show port movements and METEO/oceanographic conditions to NAVOASPOF Castro

Experimental study beginning

Briefing Room – before series

- Welcoming and briefingASPOF Castro
 - Distribute study information leaflet.....ASPOF Castro
- Distribution of:
 - Confirm demographic forms reception/fillingASPOF Castro
 - Confirm consent form reception/fillingASPOF Castro
 - Distribute and brief TiA questionnaireASPOF Castro
- Inform teams that after series they return to briefing room.....ASPOF Castro
- Inform that interaction with investigators or SIMNAV operators is not allowedASPOF Castro

Bridge – Before series

- Teams go to the bridge and setup.....ASPOF Castro
- NAVO begins pilotage briefingASPOF Castro

- Initiate recording of 3 cameras and DictaphoneASPOF Castro
- Check if operator is ready to begin seriesASPOF Castro
- Ask NAVO when ready to say out loud "Ready to begin series"ASPOF Castro
- Make sure series beginning sounds on the loudspeaker and initiate 2 chronometersASPOF Castro
- Leave the first chronometer with the operatorASPOF Castro

Bridge – Series ongoing

- Accompany series from the bridgeASPOF Castro
- When 2 minutes away from 2nd leg go to control roomASPOF Castro
- Open degrees to decimal lat/long converterASPOF Castro
- Get the data of position, new heading and speedASPOF Castro
 - o Lat(^o) = Long(^o) =
 - o Lat(.) = Long(.) =
 - o Heading = Speed =
- Instruct to spoof 600jj with direction in accordance with NAVPLAN in 2min.....ASPOF Castro
- Input data in NMEA simulatorASPOF Castro
 - o Click override of heading and speed on the simulator panel
 - o Make sure GPS is turned on and mute button is off
- Initiate spoofing at 0 time, beginning of 2nd legASPOF Castro
- Immediately switch cables in GPS input from instructor to NMEA SIMASPOF Castro
- Accompany series from the control roomASPOF Castro
- If there are a total of 6 legs, adjust course in NMEA SIM for 3rd legASPOF Castro
- When 1 minute away from 3rd leg, coordinate with operatorASPOF Castro
- Operator initiates SAT DEF + REC DEF in instructor at 0 timeASPOF Castro
- Operator turns AIS offASPOF Castro
- Initiate jamming on NMEA simulator by clicking muting GPS.....ASPOF Castro
- Accompany rest of series from the bridgeASPOF Castro
- Make sure the series ending sounds in the loudspeakerASPOF Castro
- Stop 2 chronometersASPOF Castro

Bridge – After series

- Take a picture of the chartASPOF Castro
- NAVO does pilotage debriefASPOF Castro
- Store the 3 cameras and the dictafoneASPOF Castro
- Receive and store the position registry by the operatorASPOF Castro
- Switch off cables from technological solution in the backstageASPOF Castro
- Suspend the computer connected to it.....ASPOF Castro
- Thank the team and coordinate exit from the bridge with the evaluatorsASPOF Castro

Briefing room – After series

- Welcome team in briefing roomASPOF Castro
- Distribution of:
 - o Distribute and brief NASA-TLX.....ASPOF Castro
 - o Distribute and brief SARTASPOF Castro
 - o Distribute and brief GNSS information-dependent systems questionnaireASPOF Castro
 - o Distribute and brief transitive memory questionnaireASPOF Castro
- Thank everyone for participating and wish successesASPOF Castro
- Stress the importance of not sharing detailed info about the studyASPOF Castro

Wrapping-up

- Collect and store all questionnaires and forms in respective folder.....ASPOF Castro
- Collect pointer and pen driveASPOF Castro
- Thank control room and others who have cooperated with the series.....ASPOF Castro
- Depart CITAN.....ASPOF Castro
- Attribute the adequate coding to all questionnairesASPOF Castro
- Store all questionnaires in the study's archive.....ASPOF Castro
- Store video and audio records in accordance with storing plan and naming protocolASPOF Castro
- Store chart pictures in accordance with storing plan and naming protocol.....ASPOF Castro
- Check and recharge battery of all technological resources (cameras and dictaphone) ...ASPOF Castro
- Process all data collected through the purpose created sheets and documentsASPOF Castro

Annex IX - Technological solution adapted

The coupling between the ECDIS positioning input and the instructor GPS source had to be physically changed from the bridge to the server room through an extension.

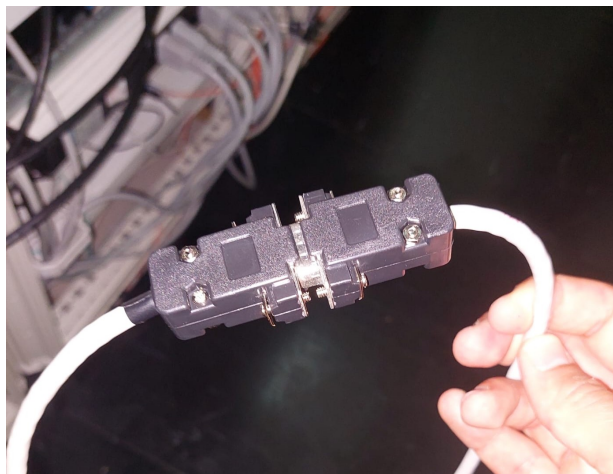


FIGURE IX.1: Coupling between the ECDIS positioning input and the instructor GPS source

Before introducing a false spoofing solution in the equipment (previously calculated through the purpose-made Python script), the parameters were introduced in the NMEA simulator, which was installed on a computer in the server room.



FIGURE IX.2: The new computer with the NMEA Simulator software open

For the spoofing to take effect in the equipment, at the time previously coordinated with the Polaris Instructor operator, the coupling was changed from the instructor GPS source to the NMEA simulator, disconnecting the cables and connecting the ECDIS positioning input to the computer.

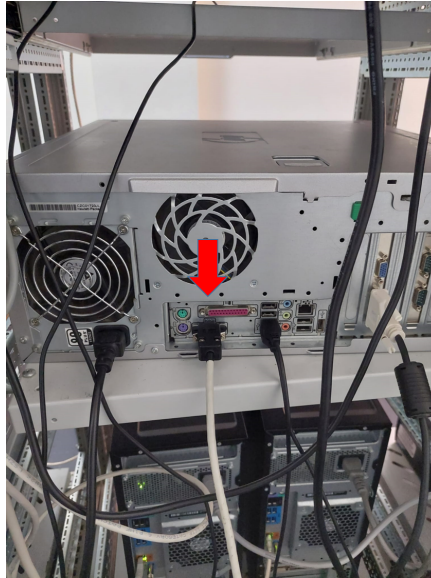


FIGURE IX.3: ECDIS positioning input connected to the computer with the NMEA Simulator

Annex X - Spoofing position calculator

lat_long_prob_v4

July 12, 2022

```
[1]: import math

#Parametrização

brng_normal = 350
speed = 25 #knots
lat0, lon0 = u'''38°00'00"N, 9°00'00"W'''.split(', ')
time_min = 120
brng_off_normal= 45
d_off_m = 600

#Fórmulas

def conversion(old):
    direction = {'N':1, 'S':-1, 'E': 1, 'W':-1}
    new = old.replace(u'°',' ').replace('\'', ' ').replace('\"', ' ')
    new = new.split()
    new_dir = new.pop()
    new.extend([0,0,0])
    return (int(new[0])+int(new[1])/60.0+int(new[2])/3600.0) * direction[new_dir]

lat0=conversion(lat0)
lon0=conversion(lon0)
R = 6378.1
brng_off = math.radians(brng_off_normal)
brng = math.radians(brng_normal)
time = time_min/60 #hours
d_miles= speed*time #miles
d_yards= d_miles*2025.37183
d = (d_yards*0.9144)/1000;
d_off = d_off_m/1000
```

```
lat1 = math.radians(lat0)
lon1 = math.radians(lon0)

lat2 = math.asin( math.sin(lat1)*math.cos(d/R) +
                 math.cos(lat1)*math.sin(d/R)*math.cos(brng))
lon2 = lon1 + math.atan2(math.sin(brng)*math.sin(d/R)*math.cos(lat1),
                        math.cos(d/R)-math.sin(lat1)*math.sin(lat2))

lat3=lat2
lon3=lon2
lat4 = math.asin( math.sin(lat3)*math.cos(d_off/R) +
                 math.cos(lat3)*math.sin(d_off/R)*math.cos(brng_off))
lon4 = lon3 + math.atan2(math.sin(brng_off)*math.sin(d_off/R)*math.cos(lat3),
                        math.cos(d_off/R)-math.sin(lat3)*math.sin(lat4))
lat4 = math.degrees(lat4)
lon4 = math.degrees(lon4)

#Resultado

print(lat4)
print(lon4)
```

```
38.82287358274519
-9.180498956355066
```

[]:

Annex XI - FRAM model of piloting

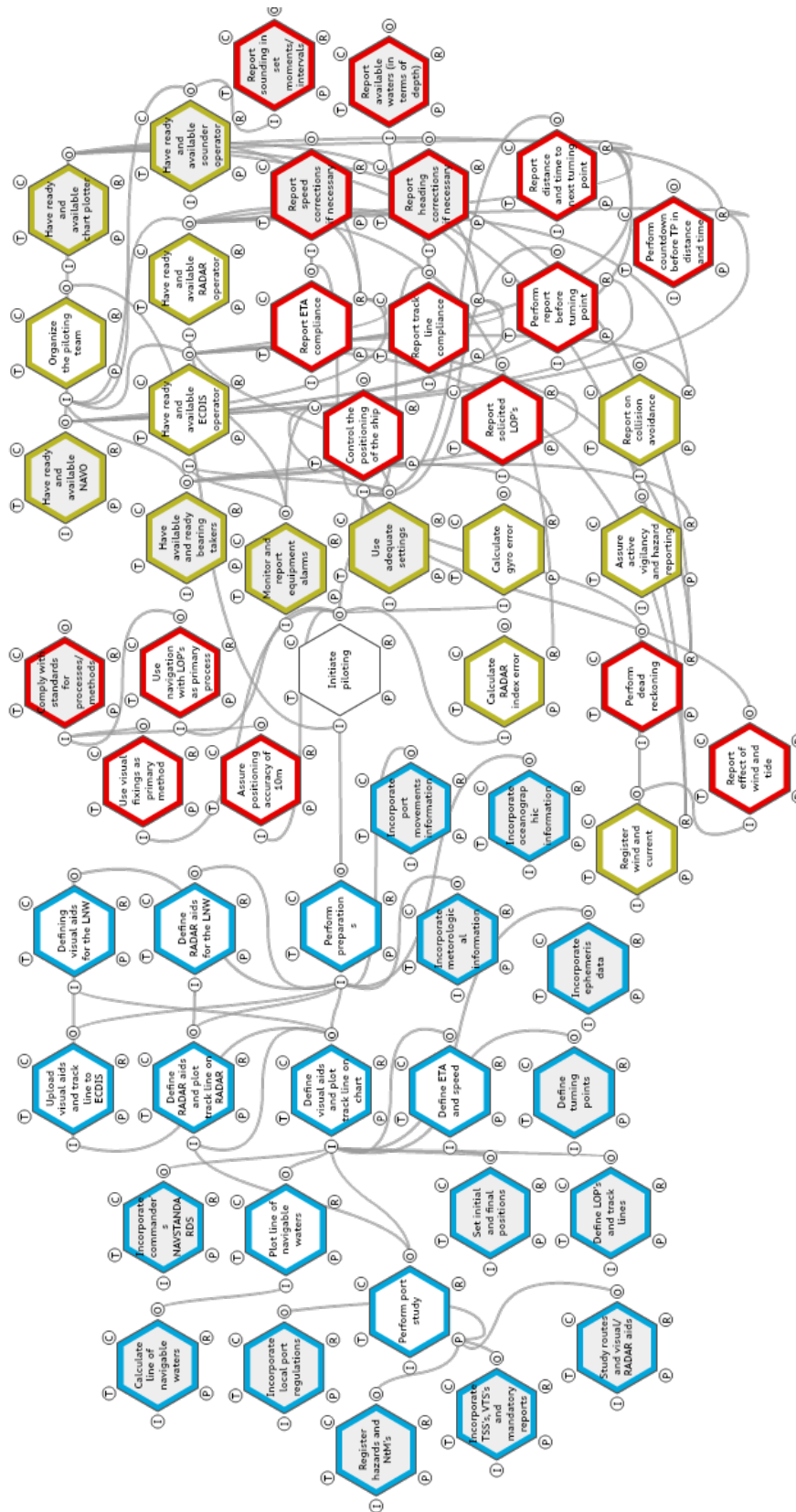


FIGURE XI.1: FRAM Model of piloting