DESIGN, ANALYSIS, AND MANUFACTURING OF A MULTIFUNCTIONAL PARALLELOGRAM GANGWAY MECHANISM

by

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ABSTRACT

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Keywords: gangway, parallelogram mechanism, finite element analysis (FEA), kinematic and force analyses

Gangways are temporary access bridge systems used in sea and air vehicles, that allows passengers to transfer safely between a vehicle and land. Especially in order to provide an aesthetic appearance on yachts, internally mounted and telescopic openable types of gangways are preferred. For this purpose, a gangway is mounted inside a space opened into the hull, particularly at the top of the ladder connecting the decks of the boat. Depending on the distance between the boat and pier in boarding position, the size of the gangway and its mechanism differs. In the case of long gangways, the number of telescopic stages and/or the size of parts and occupation of extra volume of retracting mechanism (for hiding the gangway) are the limiting factors in realizing feasible gangway use on space-limited yachts. This thesis work focuses on improving stacking efficiency and adding functionality to the box type (internally mounted) of gangway prevalent in superyachts.

For this purpose, a new multifunctional ergonomic gangway with a parallelogram mechanism was developed and manufactured to remedy the aforementioned problems. This gangway also serves as a ladder between decks, thus retaining functionality when it is not used as a gangway. Furthermore, the gangway stands on the deck and the extension starts from the end of the ladder, whose pieces comprise gangway; thus, the required length of the gangway is managed regardless of limited hull space.

At the beginning of the development process of the gangway, the conceptual design of the mechanisms was formed with rigid body links. The detailed working principles of the mechanisms were explained, and degrees-of-freedom (DOF) of each simplified mechanism were calculated. To obtain design parameters such as the length of links, the distance between them and their angles for 3D modeling, the kinematic analysis was studied by the analytic approach, and the equations were solved by MATLAB. Based on the obtained data, the 3D model of the assembly was designed considering the manufacturing process using a computer-aided-design (CAD) program. Then, the static analysis of the gangway was performed with finite element analysis (FEA) using ANSYS Workbench (Static Structural module) software. The final design of the gangway was achieved based on the kinematic and static analyses results considering DNVGL-ST-0358 regulations. Due to the difficulties of accurately calculating required actuator forces in complex assemblies, ANSYS (Rigid Body Dynamics module) was used and the appropriate hydraulic actuators were selected according to the force and kinematic analysis results. Furthermore, the obtained analytical results were validated by comparing them to the results obtained using ANSYS. Finally, the manufacturing of the gangway was completed and applied to the yacht.

ÖZET

ÇOK FONKSİYONLU PARALEL PASARELLA MEKANİZMASININ DİZAYNI, ANALİZİ VE ÜRETİMİ

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MEKATRONİK MÜHENDİSLİĞİ YÜKSEK LİSANS TEZİ, TEMMUZ 2020

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Anahtar Kelimeler: pasarella, paralel mekanizma, sonlu elemanlar analizi, kinematik ve kuvvet analizleri

Deniz ve hava araçlarında kullanılan pasarellalar (geçit merdiveni) yolcuların araç ile kara arasında güvenli bir şekilde transferini sağlayan geçici köprü sistemleridir. Özellikle yatlarda estetik görünümün sağlanabilmesi için dâhili olarak monte edilen ve teleskopik açılan tipteki pasarellalar sıklıkla tercih edilmektedir. Bu amaçla tekne gövdesi içinde özellikle geminin güverteleri arasında geçişi sağlayan merdivenin üstünde açılan bir boşluğa monte edilmektedir. Teknenin yanaştığı pozisyonda kara ile olan mesafesine bağlı olarak nispeten daha uzun pasarellalar gerektiğinde teleskopik kademelerin sayısının veya parçaların boyutunun artırılması ve sistemi gizlemek için kullanılan açma-kapama mekanizmasının da bu boşlukta yer alarak fazla hacim kaplaması pasarellanın yer kısıntısı olan tekne gövdelerine uygulanmasını oldukça zorlaştırmaktadır. Bu tez çalışmasında çoğunlukla yatlarda kullanılan kasalı (dâhili) tip pasarellaların istiflenmiş verimliliğinin ve fonksiyonelliğinin artırılması üzerinde durulmuştur.

Bu amaçla, yeni çok fonksiyonlu paralelkenar çubuk mekanizmalı ergonomik pasarella geliştirilmiş ve üretilmiştir. Bu pasarella kullanılmadığı durumda güverteler arası geçişi

sağlayan merdiven görevini de üstlenerek fonksiyonellik kazanmıştır. Üstelik pasarellanın gizlendiği boşluk güverte yüzeyinde ve teleskopik parçaların başlangıç noktası merdivenin sonunda yer aldığından istenilen uzunluktaki pasarellalara yer kısıntısından bağımsız ulaşılabilmektedir.

Yeni bir pasarella geliştirme sürecinin başında, sistemin kavramsal dizaynı çubuklarla şematik olarak oluşturulmuştur. Mekanizmaların çalışma prensipleri ayrıntılı olarak açıklanmış ve her birinin serbestlik dereceleri hesaplanmıştır. 3B modellemenin gerçekleştirmesi için çubukların uzunlukları, birbirleri arasındaki mesafe ve açıları gibi gerekli dizayn parametrelerini elde etmek amacıyla analitik olarak kinematik analiz sağlanmış ve denklemler MATLAB yardımı ile çözülmüştür. Elde edilen verilere göre sistemin 3B tasarımı üretim yönetimleri de dikkate alınarak bilgisayar destekli tasarım programı ile dizayn edilmiştir. Ardından, modelin statik analizi sonlu elemanlar analizi ile ANSYS Workbench (Statik Yapısal modülü) programı kullanılarak gerçekleştirilmiştir. Pasarellanın nihai tasarımı, ilgili kurallar (DNVGL-ST-0358) dikkate alınarak kinematik ve statik analizler sonuçlarına göre tamamlanmıştır. Çok sayıda bileşenden oluşan sistemde aktüatörler için gerekli kuvveti hassas bir şekilde hesaplamadaki güçlükler nedeni ile ANSYS (Katı Cisim Dinamiği modülü) programı kullanılmıştır. Kuvvet ve kinematik analiz sonuçlarına göre uygun hidrolik pistonlar seçilmiştir. Üstelik analitik olarak elde edilen kinematik analiz sonuçları da ANSYS sonuçları ile doğrulanmıştır. Son olarak, pasarella üretilmiş ve teknede uygulanmıştır.

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to my family

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SOLAS: Safety of Life at Sea

DOF: Degrees of Freedom

1. INTRODUCTION

Transportation has been one of the most important factors in the communication of people and nations throughout history. Transportation is not only crucial for transferring people from one location to another, but it is also vital for trade, as well. With the recent developments in technology, significant improvements have been achieved in transportation both on sea, land, and air routes. Furthermore, transportation durations that last for days have been reduced to hours or even minutes.

Sea transport has been widely used especially in international transportation. Around 90% of the world trade is carried out by sea transportation [1]. The main elements of the maritime transport are sea vehicles and ports. Vessels such as oil tankers, bulk carriers, general cargo, containers, ferries, and cruise ships contribute to the national economy with domestic and foreign transportation [2].

The advantage of transporting large quantities of raw materials or cargoes at a time, as well as the cost of transportation being the cheapest compared to rail, land, and air, are among the significant advantages of maritime transport. In addition to being safe and economical, it is the most carbon-efficient freight and passenger transportation method [3, 4]. As a result, maritime transportation has become a strategic sector in global trade. In today's world, maritime is not only defined as a type of transportation in parallel to the increase in global trade volume and rapidly developing information and communication technologies but also consists of the shipbuilding industry, port services, live and inanimate natural resources, the management of the marine environment, marine tourism, and yachting [5].

Shipbuilding is one of the oldest industries. The first boat evidence was found in Egypt by at least 4000 years BC. The boats of the River Nile constructed with reeds and featured with paddles turned into sailing boats to utilize wind power. Then, the boats were reinforced with a wooden structure to withstand sea conditions. Moreover, long steering oars and rope controlled improved sails were developed to gain maneuverability. Several factors become distinctive to design ships such as speed, maneuverability, and durability for warship and high volume load capacity and seaworthiness for trade and explorer vessels [6]. On the other hand, the yacht was introduced by the Dutch as a comfortable short voyage boat in their shallow and narrow water shores. In 1660, the Dutch navy presented the first English yacht to British royalty; hereby, it became a symbol of luxury. Moreover, speed and stylish yachts enabled a new sport for the race of Kings and noblemen. In the 19th century, yachting had grown all around the world with the participation of new yacht clubs [7].

Early 19th century, steam-powered engines were used in addition to wind power as a propulsion system. During this century, the application of gradually developed propellers and iron let the ships cross oceans. Then, the high tensile steel was preferred to wood as a construction material for the ship hull structure. The investigations on the steel grade and internal combustion (diesel) engine had initiated the modern shipbuilding period [8]. The lightweight and corrosion-resistant aluminum alloys contributed to reducing construction weight and achieving an increase in speed. In the last century, economical fiberglass became the pioneer of a transition from traditional to contemporary methods and enabled mass production using mold techniques. Recently, the improvements in composite materials such as resin, woven fabrics, carbon fiber and kevlar, and new technologies on marine equipment have been the basis of the revolution in the shipbuilding industry [9].

Today, superyacht building has become a dynamic and growing sector in the shipbuilding industry. Turkey has achieved the third position with the manufacturing of high-quality superyachts in the global market. The superyachts generally defined as the ultimate luxurious, professionally crewed, modern systems equipped, and motor or sailing powered vessels with a full-length higher than 24 meters [10]. A 34-meter superyacht built in Turkey with a steel hull and aluminum superstructure is shown in Figure 1.1.

Figure 1.1 34-meter superyacht [11]

The marine equipment segment is one of the important parts of the maritime industry. It has a wide range of products such as propulsion, navigation, lighting, outfitting, electrical, hydraulic, mechanical systems, cranes, and gangways. The preference of the equipment features varies depending on the type of ship. Aesthetics and ergonomics are the main features that stand out among others, especially for outdoor applications of superyachts. Among these, our scope in this thesis is the gangway applied to the superyachts.

The gangway is a temporary access mechanism between ship and pier or platform that enables the safe transfer of people. It may be produced from various materials such as wood, aluminum, steel, fiberglass, and/or carbon fiber. The actuation can be supplied using manual, hydraulic, pneumatic, and electromechanical power systems. In addition to design requirements such as the length, person, or load capacity and safety factor, the safety rules, according to SOLAS (International Convention for the Safety of Life at Sea), such as adequate walkway width, lighting, and handrails, are taken into consideration [12].

1.1. Types of Gangways

The variety of gangways depends on construction materials, mounting positions, walkway stages, assembly methods such as internal or external, extra specific purposes such as a winch or swimming ladder, and mechanisms. In this study, a new multifunctional gangway mechanism is designed and manufactured; and will be explained in detail. Contrary to externally mounted models, in internal storage models, a gangway covering box mounted inside the gap of the boat is used to hide gangways while cruising. Hence, the gangway is classified into three basic types, such as *folding*, *rotating*, and *telescopic* gangways, according to their mechanisms regarding retractable options [13].

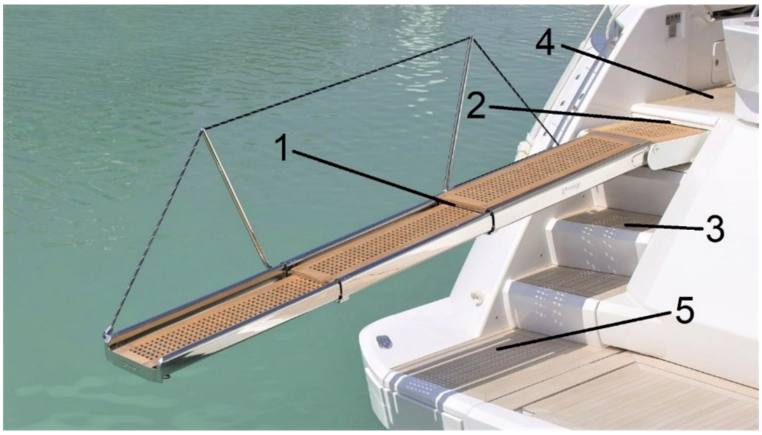

Figure 1.2 A retracting box gangway on a yacht [14]

Figure 1.2 shows the typical box retracing gangway (1) and assembly location (2) on the yacht. The gangway is mounted inside the hull at the beginning of the ladder (3) that connects the deck (4) and stern platform (5). It provides access for passengers between the deck and dock.

The novelty of the developed gangway is to enable the application of gangway to the space-limited yachts ensuring aesthetics. It is achieved that the stationary ladder turns into a movable ladder using a parallelogram mechanism and telescopic walkway cassettes are attached to the end of the ladder. This multifunctional gangway is mounted to the space of the stationary ladder on the boat while the typical retractable gangway is mounted into the hull of the boat for hiding the gangway. The parallelogram mechanism enables the gangway to be utilized as a ladder when not in use. Conversely, it provides a smooth walkway throughout ladder and telescopic gangway pieces at the same level in gangway configuration. Furthermore, longer gangway is achieved by locating telescopic pieces at the end of ladder and maintaining retracting mechanism in stern platform. (Note that extension of gangway begins at the initial of ladder and retracting mechanism occupies volume in the gangway box in a conventional gangway). Thus, the stacking efficiency of the gangway is increased and gains functionality; finally, the gangway is easily applied to the boat regardless of the hull's space. The problem of typical box type gangway and solution of the new multifunctional gangway to this problem will be explained detail in following sections (1.2 Problem Definition, 1.3 A New Multifunctional Gangway)

1.1.1. Folding Gangway

Folding gangways provide a compactness advantage due to a foldable mechanism. They are mainly used where space is limited. Figure 1.3 shows the mechanism of a typical folding gangway. Mostly this mechanism is made of two pieces (3, 4) and connected with joints in the middle of the gangway. Only in retracting models, an additional cover box (1) is used to mount the gangway inside the boat.

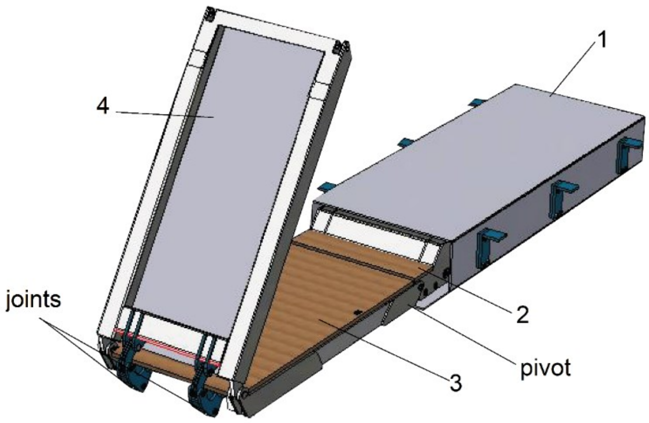

Figure 1.3 Folding gangway mechanism

There are four main parts in folding gangways: box (1), support (2), lower (3), and upper (4) sections. The box is the fixed section that enables the extracting and retracting of the gangway with actuators when not in use. The support frame is connected to the box with actuators. In external gangway models, the frame is mounted directly to the boat. It provides lowering and lifting of the gangways. The lower part is the section that is connected to the support frame via pivot mounting. The upper part is the following part of the lower section, which is connected via a hinge or bar mechanism. By the half-rotation of this mechanism, two parts can pivot relative to one between a fully extended and folded positions. Also, this mechanism is automatically locked to ensure safety passageway. In the same manner, the stages of gangways can be increased.

Due to the transverse stacking of parts, the gangway occupies a small volume when it is in the compact form. On the other hand, all stages must be opened at the same level to sustain a smooth walkway. Furthermore, it does not enable to control the required extension length.

1.1.2. Telescopic Gangway

The telescopic gangway is the most common space-saving gangway, especially on small yachts. A simple telescopic gangway has at least two parts that slide longitudinally via an actuator. Thus, the extracted length of the gangway is easily set according to the gap between the port and boat. Figure 1.4 shows the mechanism of the typical retracting telescopic gangway.

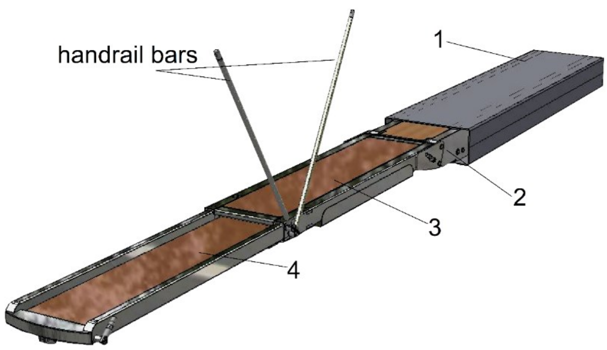

Figure 1.4 Telescopic gangway mechanism

This gangway includes four sections, namely box (1), support frame (2), first (3), and last (4) cassettes. The stationary box enables the retraction and extraction of the gangway via an actuator connected to the support frame. The support frame pivotally connected to the first cassettes enables the inclining of the gangway by linear actuators. The second cassette is longitudinally inserted into the proper housing of the first cassette. These cassettes are coupled with a linear actuator. This actuator enables the translational movement of the second cassette on a linear slide or roller system. In some models, automatically opened simple handrail can be preferred. When the gangway is extending, the handrail bars rotate from horizontal position to V-shaped position and can be associated with each other by a rope. Note that the stages of the gangway can be increased. The translational movement of each extra cassette can be sustained by adding an actuator to them. Besides, all cassettes can be opened by using a cable drive mechanism with only one actuator.

In contrast to the folding type, the precise extension of the gangway can be easily sustained. The stages of the gangway are easily increased by fitting an extra cassette into the previous one. This way, the bounding box of the gangway is longitudinally increased while transversely increased in folding type. However, this compactness is disadvantageous for a multi-staged gangway if longitudinal space is limited inside the hull for small yachts.

1.1.3. Rotating Gangway

The rotating gangway is separated from others by its rotational capability. Basically, it comprises two concentrically mated pieces, one of which is a fixed part relative to the other, and allows the movable one to rotate via a rotary actuator mechanism. Figure 1.5 shows the typical rotating gangway for the internally storable type.

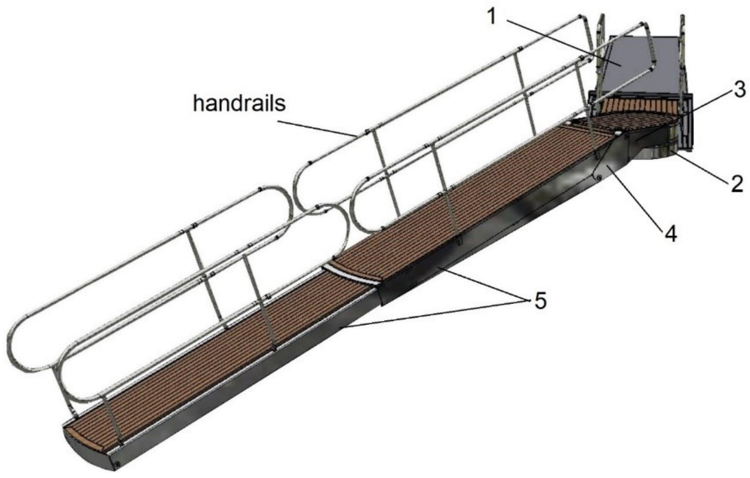

Figure 1.5 Rotating gangway mechanism

This gangway consists of five sections as box (1), support frame (2), rotatable platform (3), pivot support (4), and gangway pieces (5). The box fixed to the boat enables the extraction and retraction of the gangway via an actuator connected to the support frame. The rotary actuator positioned on the support frame is coupled with the platform coaxially. The rotation angle of the platform is limited to prevent collusion of the gangway with the boat. Also, the platform is connected to the gangway pieces pivotally (4) and provides the lowering and lifting of them via a linear actuator. The gangway pieces can comprise either one stage or more stages. In this type, telescopically opened two stages are preferred to provide a walkway. The first gangway piece attached to the platform enables the second piece to move longitudinally via an actuator. The manual fitting handrails can be used for aesthetic appearance instead of an automatic handrail.

The rotating gangway is mostly used for big yachts since it ensures parking/docking convenience. Due to the rotation capability, the yacht can dock at any orientation. Regardless of the position of the yacht, the rotating gangway can be steered to the location of the passenger landing. However, note that this gangway takes more space compared to other gangway types, thus it is not recommended for small yachts.

1.2. Problem Definition

In yacht applications, mostly internally mounted type of gangways is utilized to ensure aesthetics by hiding gangway when it is not in use. For this purpose, a space is opened in bounding box dimensions of the gangway into the hull for fitting, especially at the ladder section connecting the deck and stern platform (see Figure 1.2). If the stern platform of the yachts is large or the distance between the mounting place of gangway and dock is far; multi-staged, or relatively longer telescopic or folding parts are needed. In addition to the length of the extending parts, the retractable mechanism (for hiding gangway) occupies additional volume in the gangway box. Thus, it leads to a decrease in the stacking efficiency of the gangway. Therefore, it is not applicable to space-limited yachts.

1.3. A New Multifunctional Gangway

This study aims to increase stacking efficiency and gain the functionality to gangways. For this reason, a new multifunctional parallelogram gangway has been developed in order to overcome the aforementioned problems. Figure 1.6 shows the application of the developed gangway on the yacht.

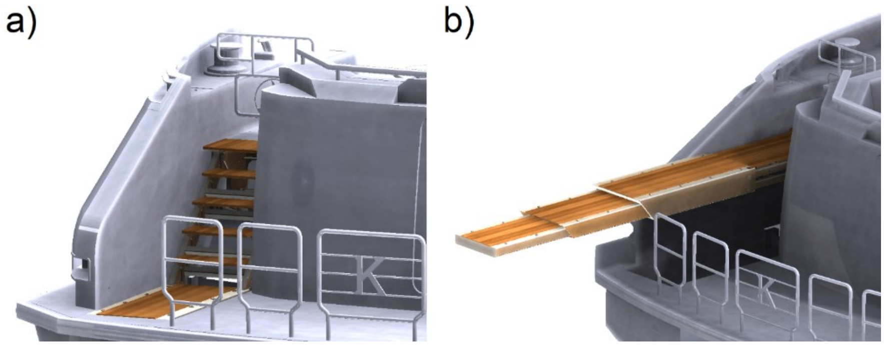

Figure 1.6 Application of developed gangway on the yacht

This product is used both as a ladder while cruising and as a gangway while docking. The box type gangway is mounted inside the hull mentioned in Figure 1.2. Contrarily, when this type of gangway is not in use, it is mounted to the gap on the stern platform at the same level. Besides, the stages of the gangway can be easily increased regardless of the limited hull space. Thus, the stacking efficiency of the gangway is enhanced. Besides, this design adds a new functionality as a ladder that connects the deck and stern platform. As a result, it provides an ergonomic design and enables weight advantages avoiding the extra ladder.

Figure 1.6-b shows the fully extended gangway. In this condition, the ladder is turned into a smooth walkway as a cassette. Contrary to the box type gangway, the extension of the stages begins with the end of the ladder that it provides more length to others.

Figure 1.7 shows the primary part sections of the multifunctional gangways: main body (1), parallelogram arms (2), platform (3), sliding cassettes (4). The design of the gangway will be explained in the following sections. Basically, the main body is assembled from the fixed and pivot points to the boat. The parallel arms section meets the ladder function that connects the main body and platform. The platform includes the sliding cassettes, and an actuator allows the translational movement of these cassettes. A cable drive mechanism is used to push both cassettes with one actuator to avoid extra actuators for each cassette. In this design, a rotating mechanism could be added, but it is not requested for this superyacht application.

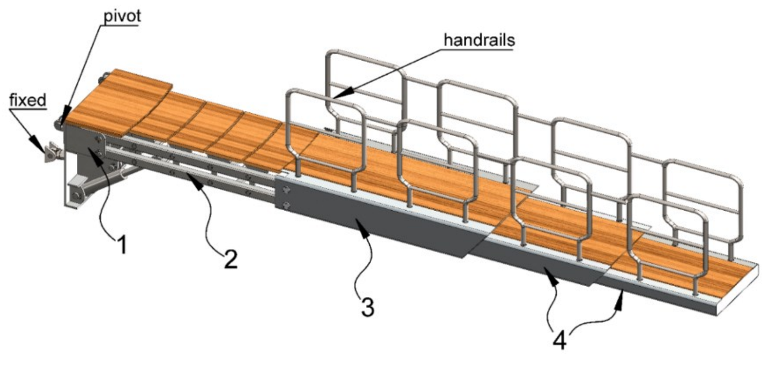

Figure 1.7 The main parts of the multifunctional gangway

Figure 1.8 shows the working stages of the new gangway. The detailed mechanisms will be explained in the following sections. First, the gangway stands on the gap of the boat (a). The parallel arms are installed in a 45° angle with the ground. Pivotally connected parallelogram arms rotate in half-quarter turn until the stairs of the arms and platform are at the same level (b). The gangway is extended until the end of the gangway is contacted with the dock (c). Also, a roller is used under the tip of the gangway to prevent the scratch of the polished cassette. Finally, lifting and lowering of the gangway is sustained according to the height of the dock (d).

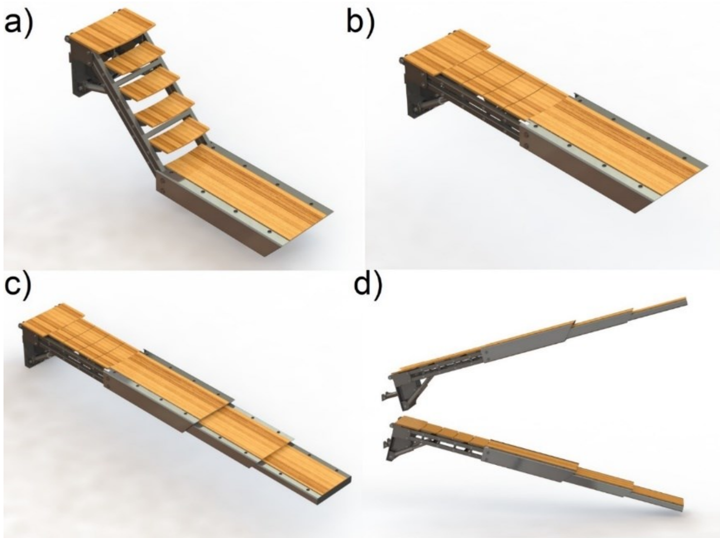

Figure 1.8 The working principle of the new gangway

2. LITERATURE

In this section, a literature review on the gangways is summarized in three segments: *(i) gangways, (ii) conducted analyses, and (iii) four-bar mechanism.* First, in Section 2.1, gangways and relevant devices have been presented. Second, the conducted analyses in a gangway design are introduced in Section 2.2. Finally, Section 2.3 covers the four-bar mechanism and shows the application of parallelogram bars in gangway design.

2.1. Literature Survey on Gangways

In this section, different gangway systems are categorized according to aspects of their capabilities, usage areas and mechanisms such as *(i) ergonomic gangways, (ii) port facilitated, (iii) positionability, (iv) self-elongating, (v) self-leveled, (vi) self-accommodated parallel gangways* and *(vii) improved locking solutions*, respectively. The deficiencies of each type and applicability to yachts are discussed and compared to the capabilities of developed multifunctional gangways.

2.1.1. Ergonomic Gangways

Over the years, a variety of gangways have been developed to meet the distinct requirements of boats in terms of various considerations such as functionality, lightness, compactness, and aesthetics, etc. depending on the type of the ship. For instance, in small vessels, weight is an essential factor, whereas for high-tonnage ships such as cruise, tanker, and container, robustness and usefulness are vital than weight. Furthermore, aesthetics, functionality, and compactness might have greater concern for yachts compared to large ships.

Due to the weight limitations of small boats, Grimaldi [15] developed a lightweight manual operated portable gangway. It comprised of two elements, a support frame and a mobile part where the vertical pin of the support frame is inserted into a hole of the boat The mobile part moves longitudinally on slide sheets of support frame, and its extension is limited by a traction cable. Thus, a removable assembled and telescopic-extended lightweight gangway is achieved.

Besides, to achieve compactness, Besenzoni [16] developed an external mounted telescopic gangway which comprises two portions longitudinally connected with linear sliding guide including cylinder rod, bearing, rod and plastic bushing which can be attached to an external surface of boat pivotally with a linear actuator, and thus, it can be folded parallel to the assembled surface to achieve compactness.

Alternatively, Sacco [17] developed a retractable telescopic gangway having the rotating capability. The box-shaped support frame of the gangway, comprising telescoping elements, mounted into a gap on a boat for concealing gangway can rotate about a horizontal axis to control inclination using a hydraulic rotary actuator. Furthermore, instead of using a hydraulic cylinder located under the gangway for a rotating gangway, this rotary actuator which is coupled with a hinge mechanism concentrically enables the gangway to save space.

Another improvement made by Franceschi et al. [18] for gangways is on the material such as a titanium structured gangway and multi-functionality as a crane. It consists of a trolley system, support frame, and telescopic elements and is attached to the boat with the trolley system longitudinally. The support frame is pivotally connected to the trolley system via hydraulic cylinders and capable of lifting and lowering the gangway. Telescopic elements are connected to the support frame and actuators of trolley systems sustain the extension and rotation of the gangway. Besides, the system can be turned into a small crane by adding a cable hoist mechanism to the end of the gangway due to lifting characteristics. Finally, the functional system can be mounted easily in compact mode on the boat for concealing the gangway. In a recent study by Yunus [19], a carbon fiber reinforced polymer composite portable gangway was designed and a prototype was manufactured. Using titanium and carbon fiber instead of traditional steel provides lightweight, corrosion resistance and eliminates the need for periodic treatment of surface painting process.

Another aspect of consideration in a gangway design is a storage option that can stand out for different purposes besides aesthetics. Especially for a cruise ship, a telescoping gangway is placed on deck in traveling, but it causes increased air resistance of ship thereby increasing fuel consumption. Rohden [20] developed a gangway to minimize air friction, and thus, fuel consumption is decreased where it is located pivotally in three-axis by winch to the gap in the side hull of the ship precisely, ensuring concealing. Due to the attaching of gangway pivotally in the longitudinal axis, it can be opened from a stowed position by winch and becomes parallel to the deck. Then, it can be rotated about the vertical axis to provide the same walkway level with the side door of the boat. Finally, it rotates about the horizontal axis, and the inclining of the gangway is arranged until the end of the gangway is connected to the dock for access.

To sum up, according to the literature, gangways which are mounted inside the boats are preferred for yacht applications to provide aesthetics rather than externally mounted ones ([15], [16], [19]). However, the requirement for space to conceal the gangways ([17], [18], [20]) in the hull effects the design of the boat and it could be difficult for space-limited yachts due to its assembly location (as mentioned in Section 1.2 Problem Definition). Furthermore, the addition of the retracting mechanism leads to a decrease in stacking efficiency in gangway volume.

2.1.2. Gangways as Port Facilities

Gangways are not only maintained in a ship but also deployed in ports. These gangways are used as a port facility for airplanes and ships and enable embarking and disembarking of goods and passengers. Hone et al. [21] developed a gangway which consists of two pieces coupled with a round room and connects the boat and terminal. The first one has an elevating system that enables the changing slope of the gangway according to airplane or ship and port terminal height. The second one has a telescopic extension and rotating driving systems. Worpenberg and Scharf [22] developed a telescopic and rotating gangway, including tunnel elements with two gates, to enable passengers can disembark from both rear and front door. In a recent study, a positionable gangway supported at the port with movable carrying ramps was developed by Bonet [23]. It consists of a movable telescopic gangway and a rotating platform with a vertical motor-less lifting mechanism to adjust the height of ramps. Thus, the gangway height is accommodated with respect to the ship level by ramps. As a result, regardless of the location of the stationary port terminal building, the boats can be docked, and gangway can be located easily. As introduced above, such applications are suitable for cargo ships due to their distinctive route. On the other hand, these gangways are not deployed in all ports and applicable for yachts.

2.1.3. Positionable Gangways for Offshore Applications

Some gangways are used for providing access between ships to stationary offshore platforms such as wind tribune and an oil rig. In high seas, the control and connection of the gangway could be hard due to wave effects. Therefore, positionable gangways should be improved to minimize relative motion between them, to achieve it, Prins [24] developed a telescopic extendable and rotatable gangway especially for wind tribune access from a boat. The tip of the gangway is attached to the boat with movable support ensuring movement in the vertical and horizontal axis. Another free end has a coupling device for connecting to a vertically directed mast of an offshore platform. For connection, gangway end is enclosed to the mast via maneuvrability of sailing vessel and rotating of movable support. Then movable support is temporarily fixed by a hydraulic system and the coupling device is attached to the pole by hydraulic actuators. After gangway end coupled, the gangway gains degrees of freedom to rotate about a horizontal and vertical axis, and move longitudinally. As the gangway is connected to the platform by a coupling device, the degree of freedom of gangway about the vertical and horizontal axis is released, and the gangway can be extended or rotated with the movable part. This dynamic positioning process necessary to prevent crushing of gangway to the pole due to high waves. Thus, the gangway can be assembled and controlled in heavy seas and tides.

An alternative to the complex positioning system mentioned above, a simple gangway system comprising three main elements, such as support frame, guiding assembly, and longitudinal mobile walkway, was developed by Prins [25]. The support frames are attached to either platform and boat and provide guiding systems, including pulleys and cable. Longitudinally movement of the gangway is sustained with a cable driving inside two pulleys. At least one pulley can by actuated by rotating with an electromotor. Thus, instead of a complex hydraulic and mechanic system, an easy positioning movement is achieved by a simple cable guide system and rotating actuator. Besides, to achieve secure positioning, a modular gangway support platform was developed by Fleischer et al. [26] for offshore gangway applications especially in high sea conditions. The working principle of it is that a gangway is mounted to the support frame attached to the boat which enables three rotational degrees of freedom and one translational movement. Thus, the secure positioning of the gangway can be sustained. Further to minimize relative motion between especially offshore fixed platforms and small boats, a gangway apparatus was developed by Watchorn and Eaton [27], which includes an inflatable gangway component attached on skate, and support part fixed to platform and a wire cable. The gangway is expanded to the desired size by inflating from a compact size. Then it is connected to the movable boat with the cable. Finally, the support frame enables the skate to move through the wire and provides secure access.

In a recent work, Brignola and Dumont [28] found a new solution for offshore gangway designs with clamping device to enable an easy assembly of the gangway to the offshore plant. The working principle of the device, consisting of two jaw and inflatable airbags mounted to the end of the gangway at two sides, is that when the airbags enlarge, the jaws close each other in a parallel situation to grip the pole or support object. Thus, eased mounting is sustained for gangway access. Finally, there is no need for positioning such above complex systems for yachts. They are generally docked at ports without the effects of high waves and just a simple positioning mechanism is used to ensure the same level with the port.

2.1.4. Gangways Comprising Self-Elongated Walkways

In a fixed-length rigid gangway type, which connects to two docked ships at sea, generally, one end is fixed and another end is oriented at another deck. As space is limited to steer the free end of the gangway for some boats, it needs to be fixed to another vessel. However, this rigid gangway could not be used in heavy seas due to the distance between vessels varies; therefore, it might undergo rupture. A self-accommodated gangway can eliminate this issue. The first approach was done by Wilson [29] to provide a variable walkway length by significant elongation instead of a gangway, which declines according to the ship's altitude. For this, a flexible gangway surrounds over rollers, and unused gangway hangs perpendicular to the walkway. When the ship moves away, the unused gangway will be pulled over rollers to complete lacking walkway. In this way, the gangway can lengthen or shorten. Similarly, handrail ropes are accommodated according to length via adding mass to end. An alternative to using an oversized gangway mentioned above, the elongation or shortening is provided using the elastic covered walkway in Maxson and Peterson's study [30]. For achieving this, the walkway consists of finite parts that connected each other via springs, and these parts are covered with an elastic stretched mat. Thus, the gaps that occurred in moving parts are prevented, and a safe and smooth walkway is sustained for passengers.

Unlike the fixed gangways at two ends as mentioned above, generally for yacht applications, the tip of the gangways at the port can be simply supported with rollers. Even if the end of the gangway needs to be fixed, these problems can be eliminated by telescopically translational movement of the gangway. As a result, the above designs are not necessary for yacht applications but can be ideal for long-term docked ships and the flow of passengers are not controlled (i.e. people use gangway in anytime freely)

2.1.5. Self-leveled Gangways for High-tonnage Ships

The level of the ship changes consistently due to the loading and unloading process especially for cargo ships or wave effects. Therefore, the height of the gangway needs to be accommodated according to the distance between the boat and the dock. For this purpose, a gangway arrangement was developed to perform variable inclination by Sugita

[31]. It is attached to the boat incapable of linear movement. The base point of the gangway is anchored to the dock and endpoint is mounted to the arrangement body with pivot connection. Thus, self-height adjustment is sustained by the free body movement at an angle of inclination adjustment. Mampaey [32] developed a vertically movable gangway for ships consisting of a tower, such as a particularly tanker This gangway is connected to the tower concentrically incapable of translational movement in the vertical axis and enable adjusting level according to the height difference between ship and dock. On the other hand, the swinging of the ship causes the torsional twisting of gangway fixed supported at two ends. Edge [33] developed a rotatable and free system, including roller and rails, to eliminate the twisting of the gangway during resting conditions. These products are not necessary for yacht applications, because the level difference between the loaded and unload yachts are not high as cargo ships.

2.1.6. Self-accommodated Parallel Gangways

In some gangways, self-accommodated flat walkways and electronic control systems are developed for handling level problems of the gangway and minimize the relative motion of gangway between boat and dock. In an early study, Gonzalez [34] developed a gangway connecting a floating platform to dock due to eliminating tides' effect on height difference. This structure consists of individuals many steps guided with a beam along the gangway. It is attached to the buoy from the end or near endpoints. For example, when it is assembled in a horizontal position, if tides rise or drop the platform, the gangway would be flat until the fixing point, and individual steps of other portions would ascend or descend in parallel, respectively. Lippa and Peterson [35] designed a gangway which consists of many platforms coupled to each other by hinge connections. The gangway ends are connected to boat and dock; when the level of the boat changes, the pivotally coupled platforms move vertically and in relative to each other. Thus, a series of adjacent walkway is achieved. In Patrick's study [36], a portable gangway, including leveling ladders, was developed. It is attached to the end of the boat, and the incline of it can be adjusted according to the deck, providing parallel steps. For achieving this parallelism, gear and rack systems are used at the ladders. According to the angle of the gangway, the longitudinal attached rack drives gear of steps and always provides parallel surfaces for access.

In a conventional gangway pivotally attached to the boat at one end, the lifting and lowering are sustained with rotating about the pivot axis by hydraulic cylinder. In contrast to this mechanism, a gangway that is capable of vertical movement to arrange level was developed by Spina [37]. It is mounted a support structure connected to the boat through a scissor mechanism. As X shaped bars in the scissor mechanism is pushed or pulled from bottom in slot horizontally, the system is raised or lowered. Thus, the walkway remains parallel to the boat, preventing inclination that occurred in conventional ones.

An alternative to the mechanical self-accommodated gangway, electronic control systems can be used for gangway applications. An adjustable gangway was developed by Cooley and Cooley [38] for the shore where frequently changing water levels. Its support frame is attached to the shore, and the boat is connected to the endpoint of the gangway in water. Owing to the gangway is always in water, it is made of non-corrosive fibreglass and includes a water level sensor. Finally, according to the water level, the movable gangway is operated with a motor to sustain access at the same level as the boat. Leske [39] developed an industrial robotic arm support and a control system capable of moving six degrees of freedom to minimize relative motion of gangway between boat and dock. In a recent study, gyro arrangement was developed to balance gangway by Nøstvold [40]. It consists of two elements that can be moved relative to each other. The first element is supported in a boat, and the second element mounted to the shore. The support frame includes a gimbal suspension mounting device and the second can move telescopically inside the first portion. Due to the gyro arranged support frame, the gangway remains horizontal, and wave effects can be minimized.

In yachts applications, tidal effects must be taken into consideration that the gangway end can be crushed to the dock. However, the complex and big systems (i.e. hard to hide in yachts for aesthetic appearance) as mentioned above are not necessary due to the short-period usage of the gangway. In our developed gangway a lifting mechanism is used to lift the gangway end a bit above the port to eliminate the crushing due to the tidal effects in the docking period. Furthermore, the parallelogram mechanism in the ladder enables to use of our gangway even in a long-term docking period to minimize wave effects ensuring a flat walkway.

2.1.7. Locking Apparat for Preventing Falling of Gangways

In some self-accommodated gangways, the contact between the simply supported end and dock could be lost due to waves during resting; therefore, it is possible to gangway slip off the dock to the sea. To prevent falling of gangway, a bearing retainer structure pivotally attached to the boat was developed by Honeycutt [41]. Later, Mizell and Anthony [42] developed a locking mechanism for the track-mounted gangway to provide safe access. It consists of a brake pad, spring, and lever assembly. An operator can manually adjust and lock the gangway position by lever even on the gangway by the brake system. Moreover, this positioning locking device was improved by Lawson and Daniel [43]. A ratchet and gear mechanism is used to rotate and place gangway in desired direction and position but prevents falling of gangway to a lowered position in the unlocked state. Differently, in Reichert and Scott's [44] locking solution, a closed-loop hydraulic system was used to prevent the falling of the gangway and provide keeping gangway in the desired position. In our developed gangway, check valves are used to lock hydraulic cylinders to eliminate these problems.

2.2. Conducted Analyses in Gangways

A kinematic, force, and static analysis have been commonly utilized in the design and control processes of gangway systems. In an early study [45], a parallel mechanism consisting of a base and top platforms connecting via six hydraulic actuators was designed for motion compensated gangway system. The number of degrees of freedom of this mechanism was calculated; then, kinematic and force analyses of it were conducted. In Yu's research [46], a parallel force and position control system was developed for gangways to stabilize the contact force between the gangway tip and offshore application. By the way, the harms of uncontrollable contact force to gangway and wind tribune are prevented; moreover, positioning of small vessels for boarding is facilitated. Kinematic and static analyses of the simplified gangway and force analysis of the actuators were conducted. Due to the considering regular sea waves' effects on ship motions, this situation is not exactly applicable in oceans. Therefore, Zhiwen et al. [47] utilized six degrees of freedom vessel and two-parameter wave disturbance approach to acquire a precise control system for compensating vessel motion. This serial manipulated gangway was developed by conducting a kinematic analysis.

Merriaux et al. [48] utilized a kinematic analysis to develop a contactless control system of an automatic compensated gangway mechanism. In Stuberg and Amundsen's study [49], a kinematic analysis was conducted in the development of a control system to reduce the relative motion of a telescopic gangway. In the paper of Li et al. [50], kinematic analysis of the telescopic gangway connecting two non-stationary sea structures during rotation and extension motion was conducted numerically and experimentally. Dong et al. [51] obtained the dynamic responses and relative motions of the gangway connecting tender assisted drilling and tension leg platform for offshore applications by kinematic analysis. Genç [13] used static analysis for the optimization of a four-staged telescopic gangway design. In Yunus' design process [19], static analysis was conducted to develop a lightweight carbon fiber gangway. Finally, in Chung's paper [52], dynamic and fatigue analyses were conducted for an offshore gangway system.

In our developed gangway designs, kinematic and force analyses are used to determine the dimensions of the gangway and capacity of hydraulic cylinder respectively. Static analysis is used to meet the design requirements of safety regulations and optimization of the gangway design.

2.3. Four-bar Mechanism

A four-bar mechanism that is composed of four-links connected to each other via revolute joints is illustrated in Figure 2.1. One of the links is fixed and the other two adjacent links have the ability to rotate or swing. The links which are capable of full-rotation and oscillating are called crank and rocker, respectively. The final link that has no connection with the fixed link is called a coupler.

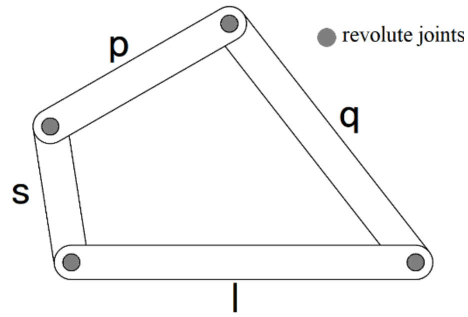

Figure 2.1 A four-bar mechanism

At this point, Grashof's rule states the motion of links according to the relationship through the link lengths. The lengths of the shortest and longest links are stated as s and l, respectively. The p and q state the other intermediate link lengths. There are three types of motion, such as double-crank, double-rocker, and crank-rocker.

Firstly, if the sum of the shortest and longest links is less than the sum of the others $(s + l < p + q)$, different types of motions can occur depending on the fixed link, as shown in Figure 2.2-a,b,c. When one of the adjacent links of shortest links (p or l), shortest (s) and opposite link of shortest link (q) are fixed, crank-rocker, double-crank, and double-rocker motions occur, respectively.

Conversely, if the sum of the shortest and longest links is greater than the sum of the others $(s + l > p + q)$, only double-rocker motion occurs, as shown in Figure 2.2-d. The opposite link of the fixed link is the coupler, and the others are rockers.

Finally, if the sum of the shortest and longest links is equal to others $(s + l = p + q)$, two common quadrilateral linkages come out, such as deltoid and parallelogram linkages. In deltoid linkage where two equal links are adjacent to a double-crank mechanism with fixed short link as shown in Figure 2.2-e and a crank-rocker mechanism with fixed long link as shown in Figure 2.2-f occurs. In parallelogram linkage where two opposite links are equal, only double-cranks mechanism occurs. For instance, Figure 2.2-g,h shows two possible inverse and parallel motions. However, when all links are collinear in both of these linkages, the rotation direction of rotating linkage is indeterminate. Therefore, a configuration is needed to prevent this motion.

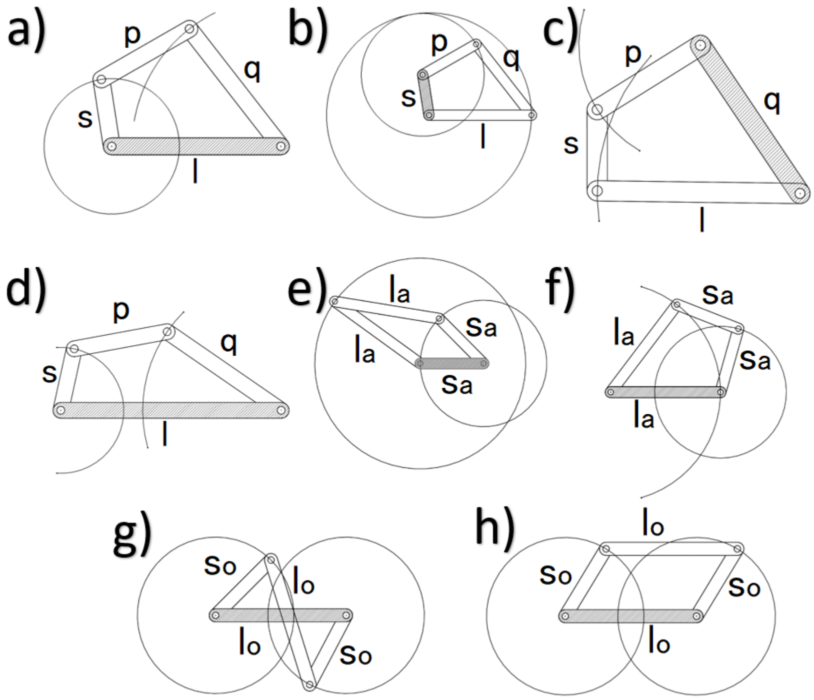

Figure 2.2 Four-bar mechanism motions

Among these linkages, a parallelogram linkage mechanism is used in gangway design as shown in Figure 2.3. Thus, regardless of the position of the cranks, a parallel walkway is sustained for a smooth transition in the ladder. This linkage consists of two short (numbered with 1,2) and two long (3,4) opposite links. The short link (1) is fixed and enables the rotation of cranks (3,4) via the driving link (5). During this motion, the coupler (2) always becomes vertical, and the horizontal top surface of this part remains parallel to the ground. Similarly, the intermediate links (6), which represent the steps of the ladder, remain parallel.

Moreover, the critical position where all links are on the same axis is not observed due to the limitation of the driving link. When a rectangular linkage is sustained (i.e. cranks remains parallel to the ground) as shown in ‘Position 2’, the system is locked. The detailed mechanism will be explained in Section 4.1.

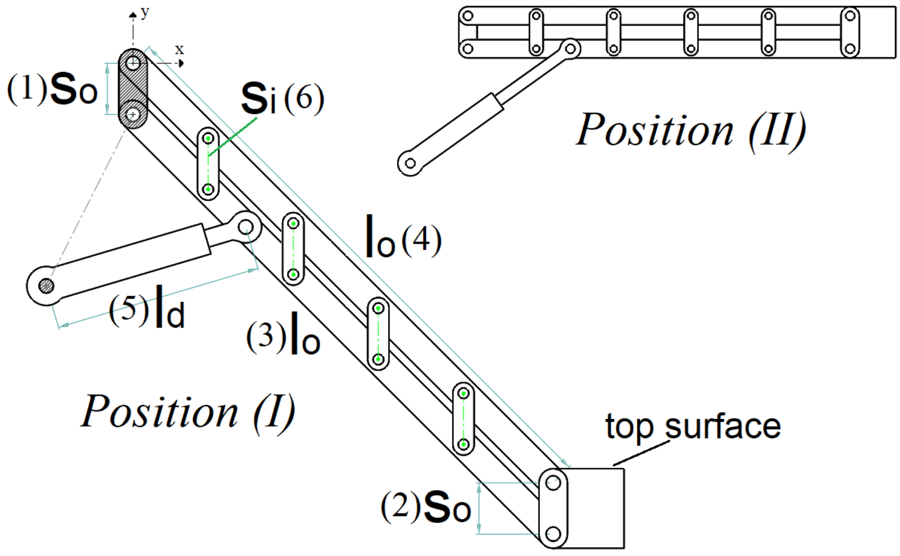

Figure 2.3 Gangway simple parallelogram linkage mechanism

3. DESIGN OF THE GANGWAY

Throughout this study, SolidWorks has been widely used as a computer-aided design (CAD) program for the 3D design of the gangway. It also enables checking the mechanism of the gangway with the assembly toolbar by defining connections between components. In addition to accomplishing design requirements, the manufacturing process is taken into consideration to optimize production cost and time. The gangway is modeled based on the static and kinematic analyses.

In this section, first, the design requirements will be explained based on guidelines (DNVGL-ST-0358) [12] and the technical requirements of the boat [11]. Then, the subassemblies and their components will be explained regarding the manufacturing processes. The gangway is designed symmetrically with respect to midplane; therefore, one side of the gangway parts will be explained. Finally, the design is categorized into three sections: main body, parallelogram ladder, and telescopic parts.

3.1. Design Requirements

Throughout this gangway design, the following requirements have been taken into consideration. According to the guidelines [12] :

- Water corrosion is a substantial factor that requires the gangway to be resistant to seawater due to the possibility of cruising in all seas.
- An inclination system is needed and the maximum operational rotating angle should be limited to ±15 degrees.

- Due to the safe transfer of people, walkway width and handrail height should be at least 0.6 and 1 meters, respectively.
- Besides, the legs of handrails should be spaced not more than 1.5 meters apart and the height difference between steps should have a maximum height of 0.24 meters.
- In normal working and emergency lift-off conditions, the gangway must have one person (120 kg) and 350 kg (equivalent to minimum of three persons while one person in a stretcher) load capacity, respectively while exceeding 1.5 and 1.1 safety factors.
- The safety length of the gangway (distance between the end point of the boat's stern point and land) should be at least 1.5 meters.

According to the boat's limitations and characteristics [11] :

- The maximum operational length of the gangway should be between 5.6 and 6 meters due to the limitation by the length of the stern platform (4.1 meters) and safety length (1.5 meters) mentioned previous requirement for safe access to the dock *(i.e. the minimum horizontal distance of gangway in full extension mode should not be less than 5.6 m during rotation of gangway to prevent a gap that may occur in the mooring position between boat and dock.)*
- The gangway's total height is arranged not more than 1.8 meters including 0.6 meters of open space in the stern platform (allowable maximum depth in the deck) and distance of 1.2 meters between decks (stern platform and upper deck) or the height of the old fixed ladder.
- The maximum width of parallelogram ladder's is limited to 0.9 meters (i.e. the width of the new ladder is arranged according to old stationary ladder's width).
- The weight of the gangway is limited to maximum one-ton according to ship stability calculations to maintain the balance of ship for better performance
- The telescopic opening of cassettes should be sustained by only one actuator.
- The extension of the gangway should be completed in less than one minute.

3.2. Main Body

The main body of the gangway system provides a connection to the boat. It is located in the space below the deck of the boat and provides the smooth operation of the ladder and cassettes, as mentioned in Figure 1.7. It also includes hydraulic pistons which enable up and down movements of the gangway and the cassettes that exit from the slot in the deck.

Figure 3.1 shows the main body parts and mounting details of the pins. The pin bearing indicated by (1) is mounted with brass bushing to ensure a concentric mate of the main body to the welded pin of the boat. Pins (2, 3) are used for connecting the upper and lower arms of the ladder section, respectively. The distance between these vertically located pins is also used for the pins of the platform to ensure a parallelogram mechanism. The pin (4) is the head joint connection of the hydraulic cylinder whose base is fixed to the boat. It enables the rotational movement of the main body about the point (1) in order to move up and down the gangway. The pin (5) is the base endpoint of another hydraulic cylinder, which provides to rotate parallel arms about points (2) and (3).

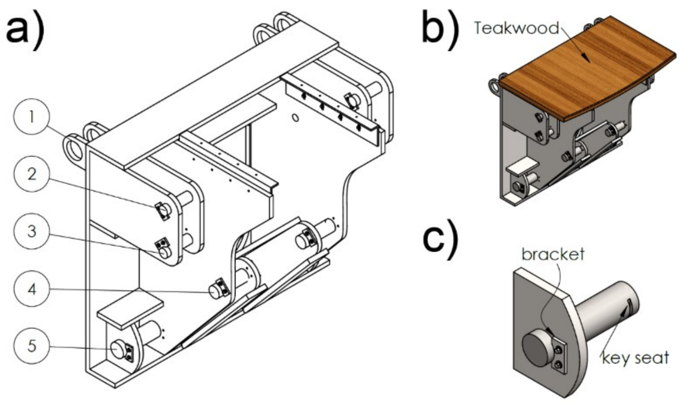

Figure 3.1 Main body and parts

Structural steel is selected as the material for the main body and it is manufactured by welding sheet metal plates. Considering visual aspects, the structure is hidden from the top with teakwood, as shown in Figure 3.1-b. The stainless steel pins are fixed to the structure with rectangular brackets by bolt connections (Figure 3.1-c). Furthermore, key seats are opened to the pins, and brackets are placed into slots. Thus, the bolt connected brackets constrain the rotation and linear movement of the pins.

3.3. Parallelogram Ladder

The second part of the gangway is the parallelogram ladder section. It is divided into three categories, as depicted in Figure 3.2 as the upper arm (a), lower arm (b), and steps (c). The structure and bushings are made of stainless steel and brass, respectively. The upper and lower arms are mounted concentrically on pins (2) and (3) of the main body and consists of four beams with a rectangular cross-section that are connected through welding. The holes are drilled on beams with precise distance intervals for the connection locations used to attach the platform and steps to the body. Then, the upper and lower arms are connected with steps via pivot pins. The teakwood plates are screwed to the sheet metal parts of the steps. Thus, the mainframe of the ladder structure is obtained, as shown in Figure 3.2-d. Throughout the design, the walkway width (width of the teakwood plate) is set to a minimum distance of 0.6 meters.

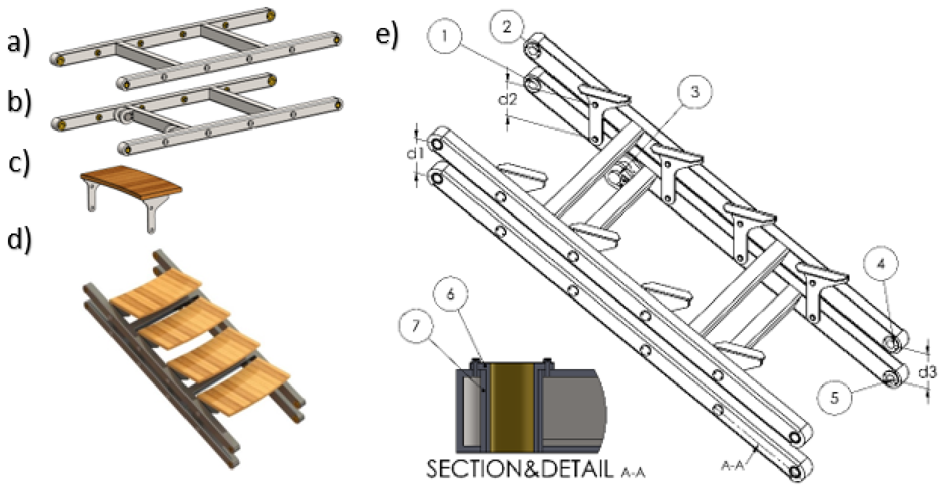

Figure 3.2 Parallelogram ladder and parts

To ensure parallelism, as mentioned above the distance between the pins on the upper and lower ladder bearings is kept constant; for instance, as indicated in Figure 3.2-e, the distance (d1) between the bushings (1) and (2) is equal to the distance (d3) between the bushings (4) and (5). The pin (3) is used to connect the hydraulic cylinder to the parallelogram ladder. This hydraulic actuator moves back and forth to force the ladder to move at an angle with respect to the deck plane (*i.e.* horizontal axis). The two holes in the steps are drilled such that the distance (d2) is equal to the distances (d1) and (d3). As a result, regardless of the orientation of the ladder, the steps remain parallel to the ground throughout the motion.

The circular hollow-section tube, as indicated by part number 7 (in Figure 3.2-e), is welded to the holes of the ladder beams. Then, the cylindrical bushing (6) in the tube (7) is fixed on the beams via bolts. Also, the pins of the steps are supported in the same method. In this way, the holes of the beams are strengthened against the pins. Furthermore, H7-j6 fitting tolerance is regarded between pin, bushing, and tube to enable smooth operation through them. Finally, the retainer rings are attached to the end of the pins to limit the linear movement of the steps.

3.4. Telescopic Parts

Telescopic parts consist of two sections: ***(i)*** platform and ***(ii)*** sliding cassettes. The structure and slideway of these parts are made of stainless steel and cast polyamide, respectively. The height of handrails which are attached to the telescopic parts both on two sides is set to 1.4 meters to meet aforementioned design requirement (handrail height should be at least 1 meter). Figure 3.3 shows the platform, which is a moving box connected to the end of the ladder via pins. When the gangway is not in use, it stands in the gap of the boat, and the teakwood (in Figure 3.3-a) is the same level as the deck to hide the gangway (see Figure 1.6-a). The outer skeleton of the platform, as shown in Figure 3.3-c, is fabricated as a box-shaped structure from U cross-section sheet metal parts (1) and (2), which are welded from the top and bottom with T and L cross-section beams (3, 4), respectively. To form U cross-section from sheet metal plate in bending machine, bending lines are determined according to bending parameters such as bending radius, angle, K-factor, and thickness. The distance between holes (d4) on the sheet metal, where pins (5, 6) are fixed, is considered according to the bushings of the ladders as indicated by (4) and (5) in Figure 3.2-e. Thus, the last link of the parallelogram is achieved. Then, cylindrical parts (7) are attached with equal distances (0.5 meters) on the sheet metal. The legs of the handrails will be placed into these holes to enable safe passage to land through the gangway. There is a linear slideway system (8, red-colored) for the cassette to move linearly inside the platform. It is formed with cast polyamide plates assembled on the sheet metal by bolts due to its low friction coefficient (0.08) and corrosion resistivity. Finally, the pivot pin (9) is attached to support the base endpoint of the hydraulic cylinder actuating the cassette.

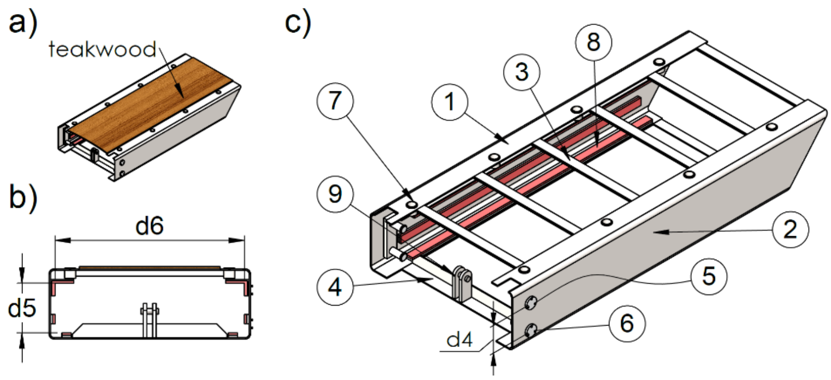

Figure 3.3 Platform and parts

Figure 3.4 shows the sliding cassettes of the telescopic parts. These cassettes enable the telescopic extension of the gangway. The structures are hidden from the top with teakwood (Figure 3.4.a,b). The structure of the first cassette, as indicated by (1) in Figure 3.4-c, is fabricated in the same way as the platform. The dimension of the boundaries is arranged according to the inner dimensions of the platform as indicated by *d5* and *d6* in Figure 3.3-b to enable smooth movement. The cylindrical part (2) is attached according to the location of the last handrail leg of the platform regarding the equal handrail distances. Also, a similar slideway system (3) is attached inside it. The pivot pin (4) is attached to support the head endpoint of the hydraulic cylinder. The pulleys (5, 6) in Figure 3.4-c are added to perform a cable drive mechanism which enables to transmit the movement of the hydraulic cylinder to the last cassette. The detailed cable drive mechanism for telescopically actuating cassettes will be explained in the following section.

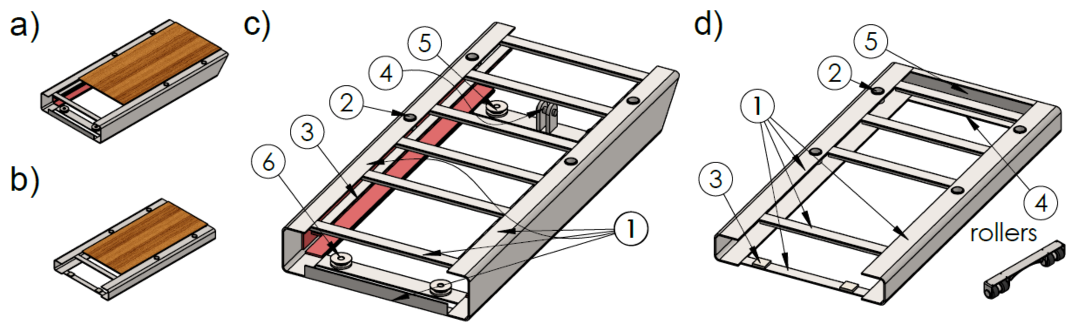

Figure 3.4 Sliding cassettes and parts

The structure of the last cassette, as shown in Figure 3.4-d, is formed with standard beams (1) and fabricated with cylindrical parts (2) similar to the first cassette. However, there is not any pulley, slideway, or pivot pin unlike the first cassette. The movement transmitter part (3) is added to actuate this cassette by cable drive mechanism. Rollers (4) are attached under the tip of the cassette to support the gangway at land and prevent the scratch of the polished steel surface. Lastly, a cover part (5) is attached to the end of the cassette to hide the inside mechanism and frames of the gangway and sustain aesthetic appearance.

4. MECHANISMS OF THE MULTIFUNCTIONAL GANGWAY

In this section, the detailed working principle of the designed gangway will be introduced. In the previous section, the essential elements of the mechanisms were mentioned. The mechanisms of the gangway are categorized into three segments: opening mechanisms I and II, and lifting and lowering mechanism. The opening mechanism I enables the transformation from the ladder configuration to the operational gangway configuration. Opening mechanism II is the cable drive mechanism that opens telescopically the gangway cassettes (with one actuator by cable drive instead of two actuators that is widely used in gangway design). The lifting and lowering mechanism adjusts the inclination of the extended gangway to achieve contact with the dock level.

4.1. Opening Mechanism I

The gangway functions as a ladder in the non-working condition that allows passage between decks on the boat. Thus, a requirement for an extra ladder is prevented that decreases the cost and weight. Point T, as shown in Figure 4.1 is the tip of the platform, and the upper surface of the platform is coincident with the deck surface. The bottom surface of the platform stands on the cut surface of the boat and supports the gangway (see Figure 1.6). The main body, fixed with the points G, H, and O, allows the parallel arms to rotate around the points K and L. The base and head endpoints of the hydraulic cylinder-1 are pivotally attached to the points P and Q, respectively. This actuator controls the angle of the parallel arms (*i.e.*, the angle of the ladder arm with the horizontal axis) indicated by α. The pins of the platform are concentrically connected to the end of the parallel arms at points R and S. The distance between points K and L is equal to the distance between points R and S; therefore, the parallelogram mechanism is established.

In this way, the platform always remains horizontal (parallel to the ground) regardless of the angle α. Moreover, the steps are attached in the same way; for instance, the third step is connected to parallel arms with pivot pins at points M and N. Thus, the steps are always parallel to the ground, as well. When the hydraulic cylinder-1 is fully extended (corresponds to $\alpha = 0$), the upper surfaces of the main body, steps, and the platform are on the same level. In this configuration, the mechanism is transformed into a gangway that allows a smooth walkway for passengers.

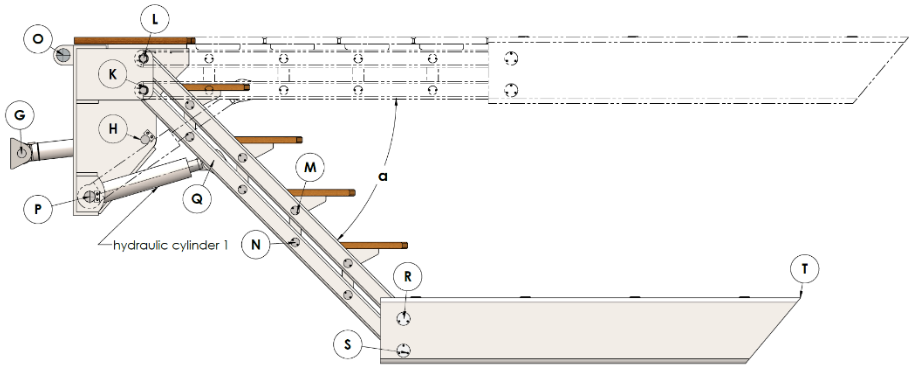

Figure 4.1 Side view of the gangway transforming mechanism

The simplified planar mechanism contains six bodies and seven joints, as shown in Figure 4.2. The body 1 (upper arm) and body 2 (lower arm) are connected to the ground by revolute joints 1 and 2 at points L and K, respectively; and coupled with the body 3 (platform) using revolute joints 3 and 4 at points R and S, respectively. Body 5 is the base part of the hydraulic cylinder and connected to the ground through joint 6. The rod of the hydraulic cylinder constitutes body 4. It provides a connection between the body 5 and body 2 by the prismatic joint 7 and the revolute joint 5, respectively.

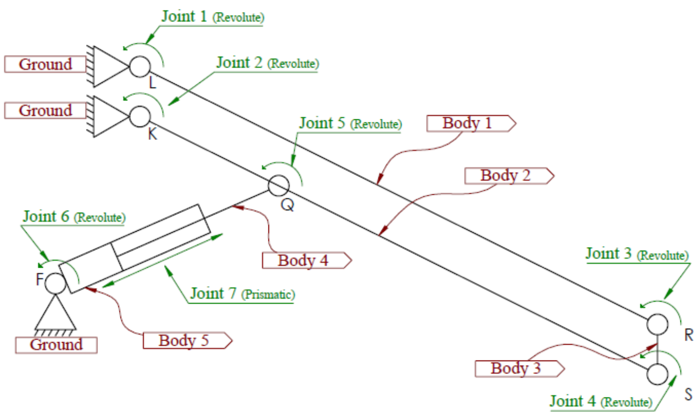

Figure 4.2 Schematic of the 1-DOF gangway-ladder mechanism

We can obtain DOF of the gangway transforming mechanism according to Grübler Equation:

$$F = 3(n-1) - 2j_l \tag{4.1}$$

where the number of the links is $n = 6$ (bodies 1, 2, 3, 4, 5, and ground); the number of 1-DOF pairs (joints 1, 2, 3, 4, 5, 6 in revolute and joint 7 in prismatic) is $j_l = 7$. Thus, the DOF in the mechanism is calculated as $F = 3(6-1) - 2(7) = 1$.

4.2. Opening Mechanism II

The gangway needs to be extended for boarding. To achieve this motion in conventional gangways, hydraulic cylinders whose size and number depends on the number and weight of the cassettes are required. However, using individual hydraulic cylinders for each cassette will increase the cost and the weight of the system. To overcome this problem, in this design, we used a cable drive mechanism, thus, one actuator is enough to move all the cassettes telescopically.

The application of the cable drive mechanism on the telescopic parts is depicted in Figure 4.3. Platform (1) is temporarily fixed to the end of the stairs section and comprises of the cassettes (2, 3). The base and head endpoints (4, 5) of hydraulic cylinder-2 are fastened to the platform and the first cassette, respectively. For instance, when the hydraulic cylinder pushes the first cassette by a distance of x, the last cassette will move $2x$ distance. Thus, the cassettes move telescopically in the same distance relative to each other.

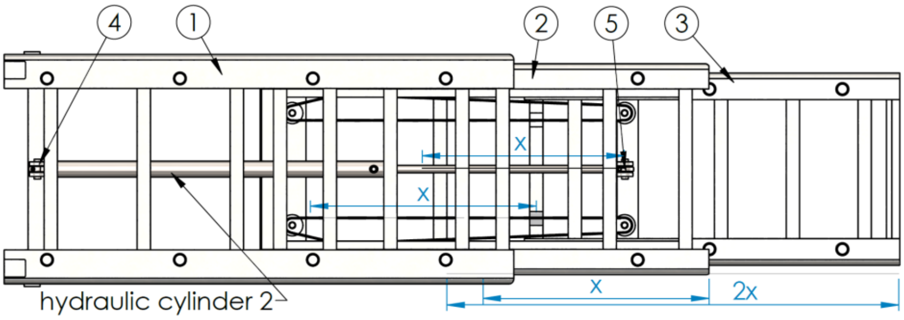

Figure 4.3 The assembly of the cable drive mechanism on the telescopic parts

The cable drive mechanism consists of two pulleys (1, 2), one stainless steel wire (3), one fixing point (4), and one motion transferring apparatus (5) as shown in Figure 4.4. The longitudinally aligned pulleys 1 and 2 are attached to the first cassette provided that the distance between them is longer than the maximum stroke length of the actuator (6). The steel wire (3) is installed around the pulleys, and tips of the wire (4) are fixed to the platform. Finally, the last cassette is fixed to the wire by part 5 with bolt connections. By the way, when the actuator pushes the first cassette, part 5 moves along the wire, thereby achieving the mechanical transmission to the last cassette. This mechanism is applied at both sides while one actuator is used in the middle to provide a smooth and balanced linear movement.

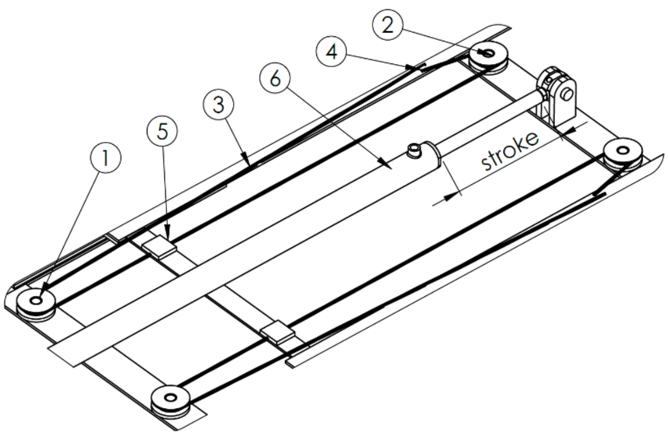

Figure 4.4 Cable drive mechanism

The simplified planar cable drive mechanism consists of five bodies and six joints. The platform is indicated as a ground in Figure 4.5 due to the temporary fixed condition for this mechanism. Body 1 is the base part of the actuator and joined to the ground with the revolute joint 1. Body 2 is the cylinder rod that is able to provide translational motion with joint 3. Its endpoint is connected to the body 3 (first cassette) with the revolute joint 2. The outer surface of the body 3 is in contact with the ground by prismatic joint 4, providing sliding in the platform (indicated by sliding area 1) for linear movement. In the same way, body 4 (last cassette) is connected to the body 3 with prismatic joint 5 (through sliding area 2). Finally, the cable drive which indicated as a chain mate in joint 6 provides line-point coupling relative motion between bodies 3 and 4.

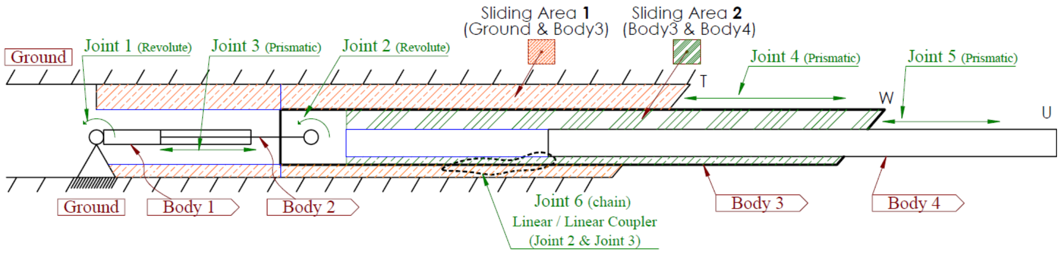

Figure 4.5 Schematic of the 1-DOF cable drive mechanism

We can obtain DOF of the cable drive mechanism according to Kutzbach Equation:

$$F = 3(n-1) - 2j_l - j_h \tag{4.2}$$

where the number of the links is $n = 5$ (bodies 1, 2, 3, 4 and ground); the number of the lower pairs (joints 1, 2 in revolute and joints 3, 4, 5 in prismatic) is $j_l = 5$ and the number of the higher pair (joint 6 in point-line contact) is $j_h = 1$. The DOF of this mechanism is calculated as $F = 3(5-1) - 2(5) - 1 = 1$. To sum up, the whole cassette system can be driven by one hydraulic cylinder.

4.3. Gangway Lifting and Lowering Mechanism

When the gangway is extended to the dock/quay, there might be a height difference between them. A lifting/lowering mechanism is introduced to handle this problem so that passengers can disembark safely. Furthermore, when the boat is docked to the pier, the gangway can always be used in full extension mode during docking. Tides cause the sea to rise and fall along the shores. It is even possible that the gangway might crush into the pier during the tides period. Thus, when the gangway is not in use, it can be lifted a little bit higher compared to the level of the pier to prevent any problems.

The gangway can rotate around point O, as shown in Figure 4.6. The base and head endpoints of hydraulic cylinder-3 are pivotally attached to points G and H, which are fixed to the boat and the main body, respectively. When this actuator pushes and retracts the main body, the gangway is lifted and lowered by rotating with respect to point O, respectively. Note that the angle of the gangway above the ground is limited to 15 degrees by the stroke length of the hydraulic cylinder.

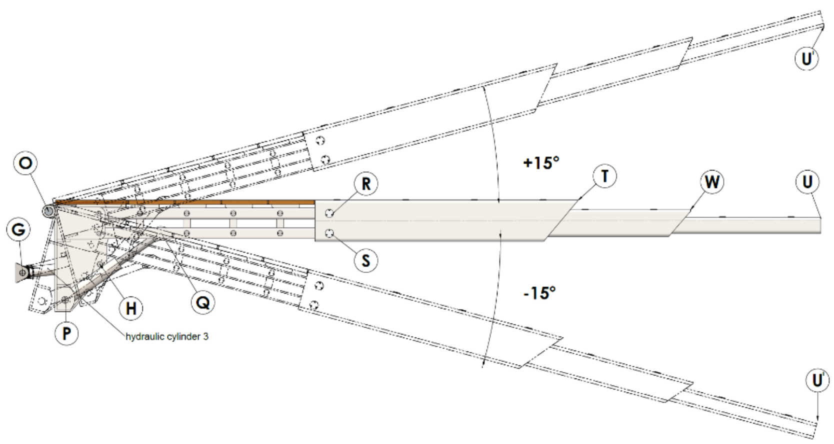

Figure 4.6 Side view of the lifting/lowering mechanism

Figure 4.7 shows the simplified lifting/lowering mechanism, including four bodies and four joints. The fixed pivot pins at points O and G indicates the ground. Body 1 is the whole gangway assembly and attached to the ground via revolute joint 1. Body 3 is the base part of the actuator and attached to the ground via revolute joint 3. Body 2 is the cylinder rod that is able to move longitudinally in prismatic joint 4. The endpoint of it is attached to the body 1 via revolute joint 2 at point H. When the prismatic joint 4 is moved back and forth, the OH line will rotate around point O.

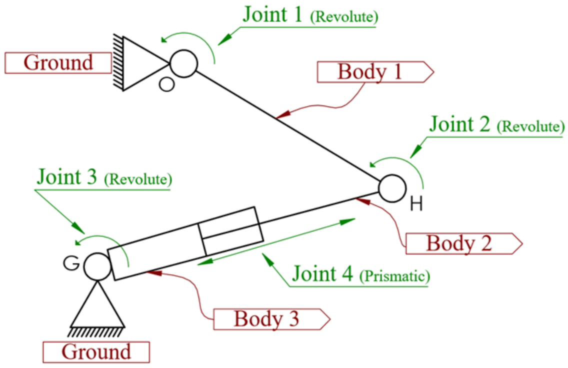

Figure 4.7 Schematic of the 1-DOF lifting/lowering mechanism

We can obtain DOF of the rotating mechanism according to Grübler Equation:

$$F = 3(n-1) - 2j_l \tag{4.3}$$

where the number of the links is $n = 4$ (bodies 1, 2, 3, and ground); the number of the 1-DOF pairs (joints 1, 2, 3 in revolute and joint 4 in prismatic) is $j_l = 4$. Thus, the DOF in the mechanism is calculated as $F = 3(4-1) - 2(4) = 1$. The DOF of the mechanism is obtained as 1; therefore, one input given by the hydraulic cylinder will rotate the gangway.

5. KINEMATIC AND FORCE ANALYSIS OF THE GANGWAY

The main purpose of kinematic and force analysis is to determine the range of movement and select an appropriate actuator to enable the motion of the gangway. In this section, the kinematic analysis is done using analytical and finite element approaches. In the first step, an analytical approach is conducted to determine the dimensions of the gangway parts. Thus, the necessary design parameters such as the length of the links, the distance between them, and their angles are selected to satisfy the design requirements that are mentioned in Section 3.1. Then, in the second step, a commercial finite element (FE) software is used for force analysis due to difficulties in accurately calculating driving forces in complex assemblies. Furthermore, analytical solutions have been validated with ANSYS results.

5.1. Analytical Approach

In the analyses, the components of the mechanism are expressed as rigid linkages; and the length of the links, the distance between them, and their angles are chosen as variables. It is noted that firstly the length of links is determined as arbitrary then they are iterated according to the design requirements and the boat space. Then, governing equations of motions are obtained. The solutions of the equations are performed using MATLAB. Finally, the ultimate design parameters are achieved using these variables. The analytical approach is applied to each type of mechanism: opening mechanism I and II, and gangway lifting/lowering mechanism.

5.1.1. Opening Mechanism I Motion

Note that the gangway system needs to be used as a ladder when it is not docked. To satisfy this criterion, a gangway ladder mechanism, as shown in Figure 5.1, is developed using a parallelogram mechanism. The links LR, RS, and KS, which constitute the parallelogram linkage loop (LRSK), are connected to the ground at points K and L. The system is actuated using the hydraulic cylinder-1 (link PQ) attached to the KS at point Q. Point T is the tip of the gangway and dictates the length of the gangway with respect to the pivot point O.

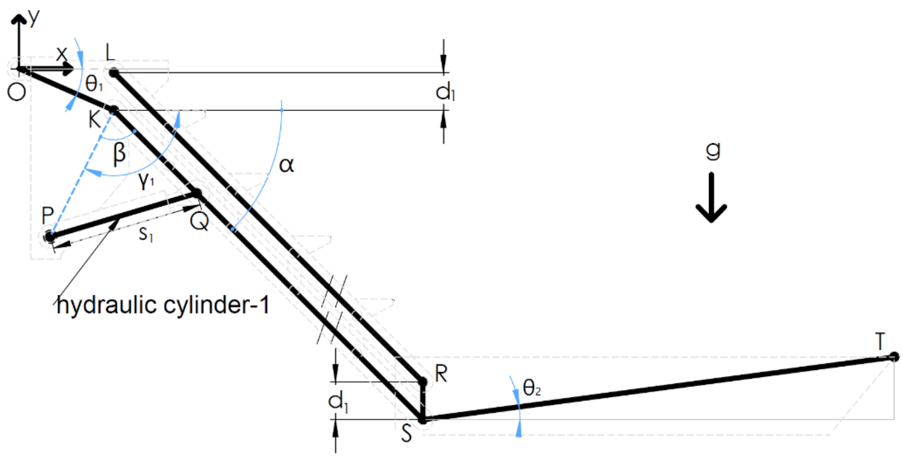

Figure 5.1 Schematic of the gangway transforming mechanism

The length of the driving link PQ is s_1, the initial length of this link is l_1, measured when the angle between the cranks LR or KS and x-axis (represented by α) is equal to π/4. The hydraulic actuator is set to move with a constant velocity (v_1). Thus, the length of the driving link PQ can be written as:

$$s_1 = l_1 + v_1 t_1 \tag{5.1}$$

The maximum length of the driving link is arranged, such that the most extended PQ length corresponds to the gangway configuration when α is equal to zero (*i.e.* the cranks LR and KS are parallel to the x-axis). Since points P and K are fixed, the angle between the line connecting points P and K, and the horizontal axis, γ_1, is constant.

KP, KQ, and PQ lengths are the links of the triangle KPQ, and the opposite angle of the PQ link is β. The angular displacement of the cranks in the four-bar mechanism is related to the stroke of the driving actuator. Therefore, the law of the cosines is used to obtain a relationship between s_1 and β:

$$s_1^2 = |KP|^2 + |KQ|^2 - 2|KP||KQ|\cos(\beta) \tag{5.2}$$

The distance and angle of the point K to pivot point O are described as OK link and θ_1, respectively. The position of the point T is determined with respect to the arbitrary point S by ST link and θ_2 angle. The length of the links can be defined as:

$$|OK| = r_1,\ |KP| = r_2,\ |KQ| = r_3,\ |KS| = r_4,\ |ST| = r_5 \tag{5.3}$$

Then, the angle β can be found using Eq. (5.2) as follows:

$$\beta = \arccos\left(\frac{r_2^2 + r_3^2 - (l_1 + v_1 t_1)^2}{2 r_2 r_3}\right) \tag{5.4}$$

The constant angle γ_1 is the sum of α and β. Thus, the angle α can be expressed as:

$$\alpha = \gamma_1 - \beta \tag{5.5}$$

Then, inserting Eq. (5.4) into Eq. (5.5) the angle α can be obtained as:

$$\alpha = \gamma_1 - \arccos\left(\frac{r_2^2 + r_3^2 - (l_1 + v_1 t_1)^2}{2 r_2 r_3}\right) \tag{5.6}$$

The total time of the movement can be obtained from Eq. (5.6). The iterative solution gives that t_1 (time) is 26 seconds (assuming that $v_1 = 10\ mm/s$) when α is equal to zero.

Considering Eq. (5.1), the maximum stroke and limit lengths of the hydraulic cylinder-1 can be obtained. Then, the position equation of point Q, which defines the head endpoint of the actuator, is written as:

$$Q(x, y) = \left(r_1 \cos(\theta_1) + r_3 \cos(\alpha),\ -\{r_1 \sin(\theta_1) + r_3 \sin(\alpha)\}\right) \tag{5.7}$$

The displacement of point Q (Q_d) is calculated by substituting its initial position ($Q(x_i, y_i)$ when $\alpha = \pi/4$) as :

$$Q_d(x, y) = Q(x, y) - Q(x_i, y_i) \tag{5.8}$$

The X and Y displacements of point Q as a function of time, is calculated and plotted in Figure 5.2.

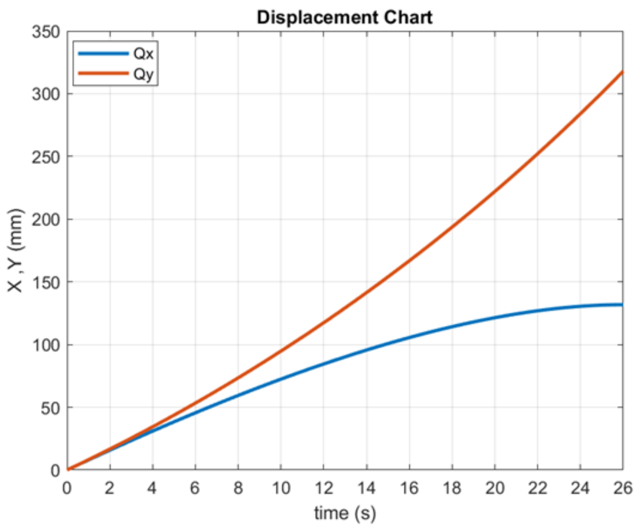

Figure 5.2 Displacement chart of point Q in x-y axes

Although the actuator provides a constant velocity, the angular displacement of the cranks is not linear. As a result, the force requirements of the driving actuator will not be constant; and thus, to select the appropriate actuator, the required force needs to be determined throughout the motion of the gangway.

The horizontal and vertical distances between the points K and O are defined by l_2 and l_3 respectively as:

$$l_2 = r_1 \cos(\theta_1), \ l_3 = r_1 \sin(\theta_1) \tag{5.9}$$

The endpoints of the cranks' points R and S are contacted with link RS of the platform. The constant vertical distance (d_1) between K and L is equal to the distance between the R and S due to the parallelogram. The positions of points S and R are obtained by the length of the link KS (r_4), α angle and d_1 distance as:

$$S(x,y) = \left(r_4 \cos(\alpha) + l_2,\ -\{r_4 \sin(\alpha) + l_3\}\right) \tag{5.10}$$

$$R(x,y) = \left(r_4 \cos(\alpha) + l_2,\ -\{r_4 \sin(\alpha) + l_3\} + d_1\right) \tag{5.11}$$

Finally, the position of point T (tip of the gangway) is obtained by the link ST (r_5) and θ_2 angle as:

$$T(x,y) = \left(r_4 \cos(\alpha) + r_5 \cos(\theta_2) + l_2,\ -\{r_4 \sin(\alpha) + l_3\} + r_5 \sin(\theta_2)\right) \tag{5.12}$$

The vertical motion of point T is calculated as a function of the horizontal motion of the same point and the results are given in Figure 5.3. The geometry of the path traced by point T, as shown in Figure 5.3, and similarly acquired geometry for the end edge of the platform are exported to develop the 3D model. The exported curvature geometry is added to the 3D boat model to determine the cutting curve for opening a slot on deck. By the way, the gangway can be attached to the slot precisely in resting position ensuring the aesthetic view of the deck with minimum gap and collision of gangway through the motion is prevented. In the following section, point S will be used as an arbitrary point to determine the full length of the gangway.

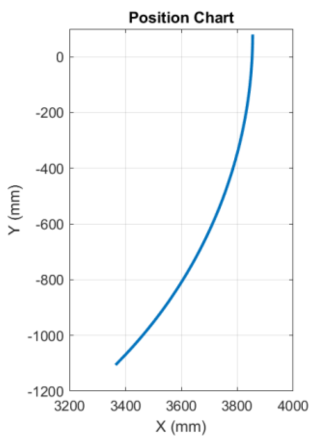

Figure 5.3 Vertical and horizontal position of point T throughout the motion during the opening mechanism I

5.1.2. Opening Mechanism II Motion

The gangway system needs to be extended when it is parallel to the ground. Note that the two stages of the cassettes should be telescopically opened via only one actuator. For this criterion, a cable drive mechanism is applied, as shown in Figure 5.4, to the telescopic parts. The points U and W are the tips of the first and last cassettes, respectively. In this study, only two cassettes are used but note that the presented system can be generalized to a larger number of cassettes. The system is actuated by hydraulic cylinder-2 attached to the first cassette. Finally, the point U' represents the endpoint of the gangway in extension mode and dictates the full length of the gangway.

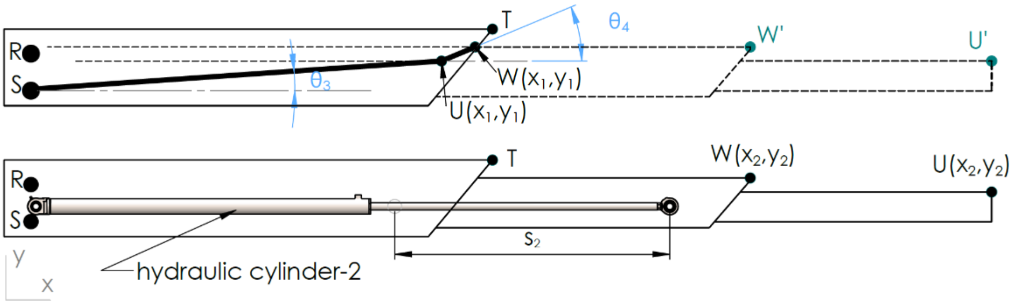

Figure 5.4 Schematic of the cable drive mechanism

The position of point U can be defined with respect to point S by vector $\overrightarrow{SU}$ as:

$$U(x_1, y_1) = S(x, y) + S\vec{U} \tag{5.13}$$

Then, using Eq. (5.10) and defining $|SU| = r_6$ and angle θ_3, we can obtain

$$U(x_1, y_1) = \left(r_6\cos(\theta_3) + r_4\cos(\alpha) + l_2,\ r_6\sin(\theta_3) - \{r_4\sin(\alpha) + l_3\}\right) \tag{5.14}$$

The initial position of point U for this motion is found by considering $a = 0$ as:

$$U(x_1, y_1)_{\alpha=0} = \left(r_6\cos(\theta_3) + r_4 + l_2,\ r_6\sin(\theta_3) - l_3\right) \tag{5.15}$$

Similarly, the initial position of point W can be found with respect to point U by link UW (defining $|UW| = r_7$) and angle θ_4 as:

$$W(x_1, y_1)_{\alpha=0} = \left(r_7\cos(\theta_4) + r_6\cos(\theta_3) + r_4 + l_2,\ r_7\sin(\theta_4) + r_6\sin(\theta_3) - l_3\right) \quad (5.16)$$

Finally, Eqs. (5.15) and (5.16) are simplified with l_4, l_5 ,l_6 and l_7 respectively as:

$$U(x_1, y_1)_{\alpha=0} = \left(l_4,\ l_5\right) \quad (5.17)$$

$$W(x_1, y_1)_{\alpha=0} = \left(l_6,\ l_7\right) \quad (5.18)$$

The stroke length of the actuator is s_2 and the hydraulic cylinder is set to move with a constant velocity (v_2) only in *x*-direction. Therefore, s_2 can be defined as:

$$s_2 = v_2 t_2 \quad (5.19)$$

The points U and W move depending on the motion of the actuator as mentioned in Section 4.2 (cable drive mechanism). Thus, the positions of points in this motion are obtained according to their initial positions (Eqs. (5.17)-(5.18) with Eq. (5.19)) as:

$$U(x_2, y_2) = \left(l_4 + 2v_2 t_2,\ l_5\right) \quad (5.20)$$

$$W(x_2, y_2) = \left(l_6 + v_2 t_2,\ l_7\right) \quad (5.21)$$

Using the above relations, based on the required length of the gangway *(according to the design criterion as arranged in the following motion, the length of the gangway is found 5.81 meters as the horizontal length of the gangway is set to be more than 5.6 meters at maximum rotation positions to enables safe transition due to the mooring position of the yacht)*, the maximum stroke of the actuator can be found. Furthermore, it is also required that the total duration of the opening/closing of the gangway should be limited under one minute. Considering these design requirements, and assuming that v_2 = 60 mm/s *(according to the piston capacity, the velocity is set to push/retract cylinder to meet the duration requirement of opening/closing gangway)*, the position of point U is plotted in Figure 5.5-a considering the motion during opening mechanisms I and II. Furthermore, during the cable drive mechanism (opening mechanism II), the horizontal positions of points U and W are plotted in Figure 5.5-b. The displacement of the point U is two times the displacement of the point W; therefore, the extension of the actuator has wholly transmitted to the last cassette by cable drive. The time of achieving full extension mode from the initial position of gangway takes 44 seconds ($t_1 = 26, t_2 = 18$).

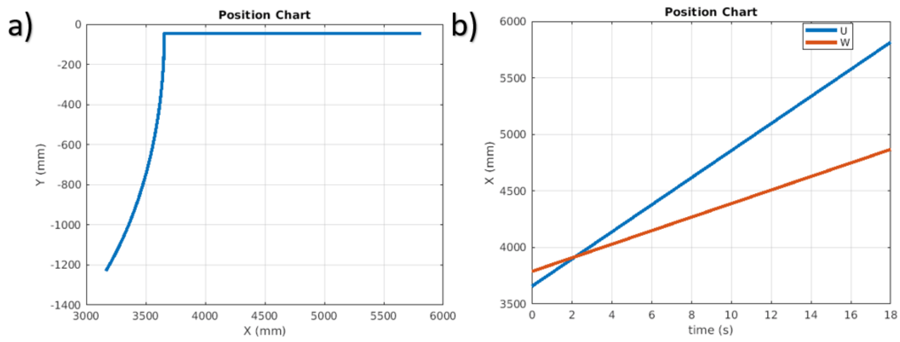

Figure 5.5 Position chart of points U and W

5.1.3. Gangway Lifting and Lowering Motion

Note that the extended gangway needs to be lifted or lowered due to height difference between the gangway and dock or due to tidal events. Figure 5.6 shows the planar lifting/lowering mechanism. The OHU triangle represents the whole gangway rotated around point O, and the tip of it is point U. The system is actuated by GH driving link connected to the gangway at point H.

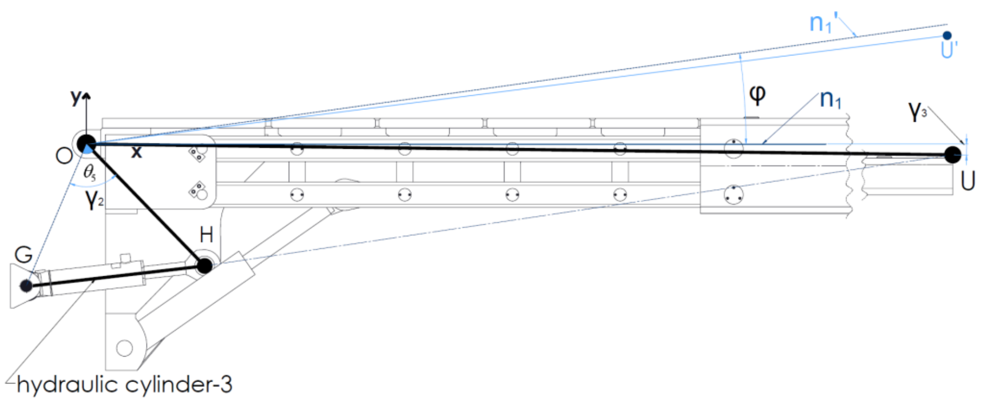

Figure 5.6 Schematic of the gangway lifting and lowering mechanism

The length of the driving link GH is s_3, the initial length of this link is l_8, measured when the longitudinal axis of gangway (n_1) is parallel to the ground. The hydraulic actuator is set to move with a constant velocity (v_3). Thus, the length of the driving link GH can be written as:

$$s_3 = l_8 + v_3 t_3 \tag{5.22}$$

The maximum and minimum lengths of the driving link are arranged such that the longest and shortest GH lengths correspond to the gangway configuration when the angle (φ) between n_1 and the horizontal axis is equal to plus and minus $\pi/12$, respectively.

OG, OH, and GH lengths are the links of the triangle OGH, and the opposite angle of the GH link is γ_2. The angular displacement of the gangway in the rotating mechanism is related to the stroke of the driving actuator. Therefore, to find a correlation of the s_3 and γ_2, the law of the cosines is used for OGH triangle:

$$s_3^2 = |OG|^2 + |OH|^2 - 2|OG||OH|\cos(\gamma_2) \tag{5.23}$$

The lengths of the links OG and OH are defined as r_8 and r_9, respectively. Then, γ_2 can be found as:

$$\gamma_2 = \arccos\left(\frac{r_8^2 + r_9^2 - (l_8 + v_3 t_3)^2}{2 r_8 r_9}\right) \tag{5.24}$$

The angle, γ_2, is defined in terms of the rotation angle φ and initial angle θ_5 due to the gangway (n_1 axis) and OH or OU link rotate together in the equal angle difference.

$$\gamma_2 = \theta_5 + \varphi \tag{5.25}$$

Finally, the limited rotation angle φ is obtained as :

$$\varphi = \arccos\left(\frac{r_8^2 + r_9^2 - (l_8 + v_3 t_3)^2}{2 r_8 r_9}\right) - \theta_5 \tag{5.26}$$

The total time of the movements can be obtained from Eq. (5.26) assuming that $v_3 = 10mm/s$ (when $\varphi = \pm 15$). Considering Eq. (5.22), the maximum stroke and limit lengths of the hydraulic cylinder-3 can be obtained. Besides, the angle control of the gangway can be sustained by stroke or time data.

The length of the OU link in full extended gangway is r_{10} and angle (γ_3) with respect to the horizontal axis is defined by the initial angle θ_6 throughout the motion as:

$$\gamma_3 = \theta_6 + \varphi \tag{5.27}$$

Finally, the position of the point U in this mechanism can be found as:

$$U(x,y) = \left(r_{10}\cos(\gamma_3),\ r_{10}\sin(\gamma_3)\right) \tag{5.28}$$

The angular displacement of the gangway, displacement of the actuator, and X-Y coordinates of the point U are calculated and plotted in Figure 5.7. Figure 5.7-a shows the stroke of the hydraulic cylinder with respect to the angle of the gangway. Using this data, the angle control of the gangway can be done based on the stroke displacement of the actuator. The X and Y coordinates of the point U are plotted in Figure 5.7-b, and the gangway can be lifted or lowered approximately 1.5 meters. Moreover, the minimum *x*-distance of the point U in full extension case occurs in the lowering motion as 5.6 meters. Thus, the design criterion is achieved that the horizontal length of the gangway in maximum operational length is not decreased below 5.6 meters during rotating motion of gangway, and a gap which may occur in the mooring position between boat and dock can be prevented. It is should be mentioned that the maximum operational length of the gangway which is obtained in previous motion is found according to this motion ensuring the minimum of 5.6 meters.

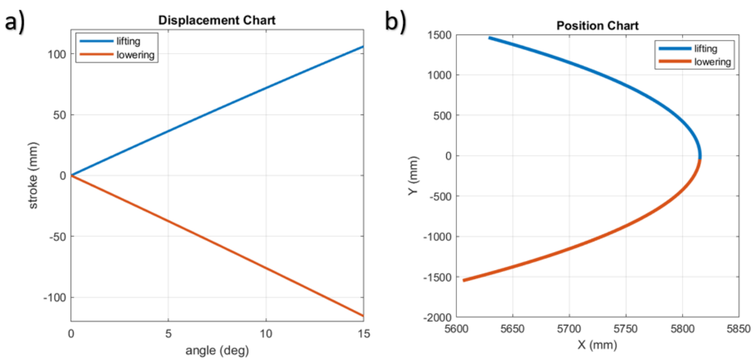

Figure 5.7 Displacement and position chart of actuator and point U, respectively

5.2. Finite Element Analysis

In this section, position and force analyses of the designed gangway system to determine the dynamic response of the gangway assembly are presented. Due to the difficulties of accurately calculating the driving forces using the analytic approaches in the case of complex assemblies, Rigid Body Dynamics Analysis toolbox of ANSYS Workbench software is used in this study.

Based on the link lengths obtained in Section 5.1, a 3D model of the gangway mechanism is constructed in SolidWorks. Then, it is exported to ANSYS, and necessary kinematic constraints are defined (such as joints). After the constraints are defined, first, the position analysis is performed to validate the analytical model (performed to decide on the link lengths). Secondly, force analysis is performed to determine the actuator forces during the motion of the gangway mechanism. This analysis is a beneficial tool that allows us to check the assembly movement visually and explore more design ideas. Figure 5.8 shows the imported assembly geometry in Workbench. At this point, the parts behavior (as rigid/flexible), materials, coordinate systems, and connections are assigned.

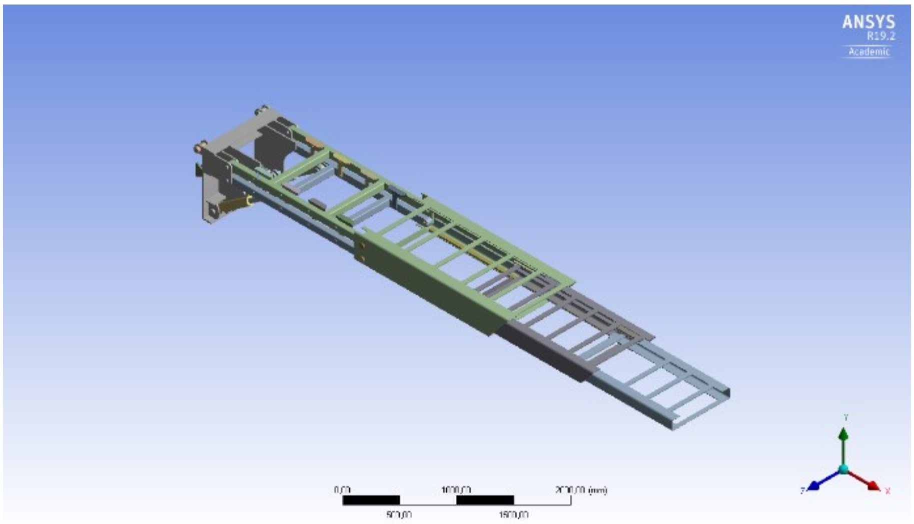

Figure 5.8 The imported gangway model (in full-open configuration)

5.2.1. Material Selection

The material selection needs to performed considering seawater corrosion resistivity, wear, strength, weldability, machining, polishability, and accessibility. Among these, water corrosion is an important issue for marine applications. The mechanical and chemical effects of corrosion on steel cause the failure of steel, as well as the appearance of rust on the stylish polished steel, harms the aesthetics of the boat. Therefore, DIN 1.4404 numbered chromium stainless steel is selected for gangway parts such as ladders and telescopic parts, and also for pins due to high strength capacity. DIN 1.0044 structural steel is selected for the main body to be easily welded to the boat. RG-7 bronze is used for bushing parts of pins. It is resistant to seawater and wear that the pins are operated smoothly. Finally, Kestlub® cast polyamide is preferred for linear guideway parts and washers that the friction coefficient is very low (0.08). Furthermore, it has a high wear and corrosion-resistantance. The selected material properties are given in Table 5.1.

Table 5.1 Materials properties

Materials	1.0044 Structural Steel	1.4404 Stainless Steel	Cast Polyamide	RG-7 Bronze
Young’s Modulus (GPa)	200	200	4	115
Poission’s Ratio	0.3	0.3	0.24	0.3
Density (kg/m3)	7850	7750	1150	8800
Tensile Strength (MPa)	460	600	80	300
Yield Strength (MPa)	250	400	80	150

5.2.2. Kinematic Constraints

The imported assembly CAD data does not include any joints, constraints, and coordinate systems in geometry transformation. Therefore, joint contacts are created to define the connections between parts for solution, and the general coordinate system is located at point O indicated in Figure 5.9.

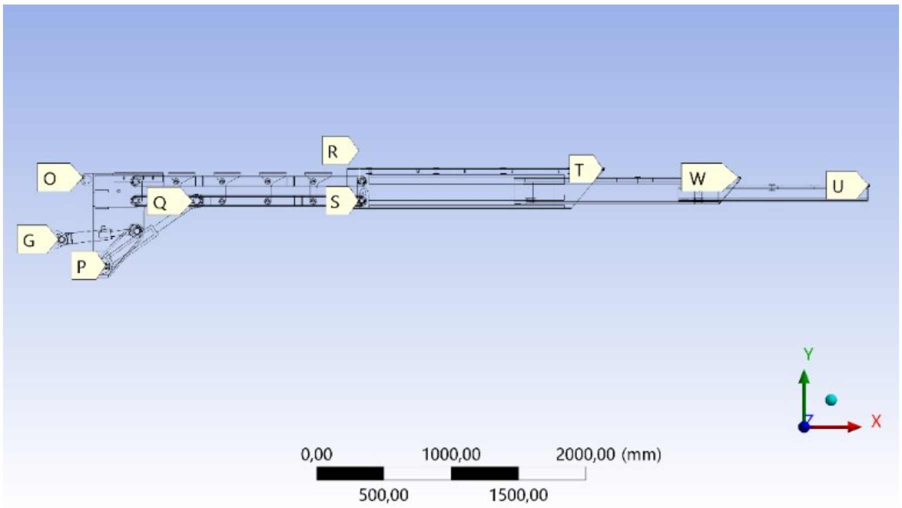

Figure 5.9 The points of the gangway assembly

The relationship between the surface to surface contacts, which automatically transformed from the geometry, can not be used; joints or springs must be defined by editing the orientation of the coordinate system of each part as a reference. The orientation of joints' coordinate systems is crucial because all joint types have the free and fixed degrees of freedom as motion through to *x*, *y*, *z*-axis (UX, UY, UZ) and rotation on *the x*, *y*, *z*-axis (ROTX, ROTY, ROTZ).

The model will be solved by assigning body-to-ground and body-to-body joints, considering their coordinate systems. In the ANSYS simulation, nine joint types are used as fixed, revolute, cylindrical, translational, slot, universal, spherical, planar, and general joints. While the joints are assigned, the reference and mobile bodies of the joints should be appropriately selected considering the actuating body and driver joint to transfer movement accurately among bodies. The bodies of the gangway assembly are defined with six degrees of freedom with their masses and moments of inertia by applying fixed, revolute, and translational joints, as shown in Figure 5.10.

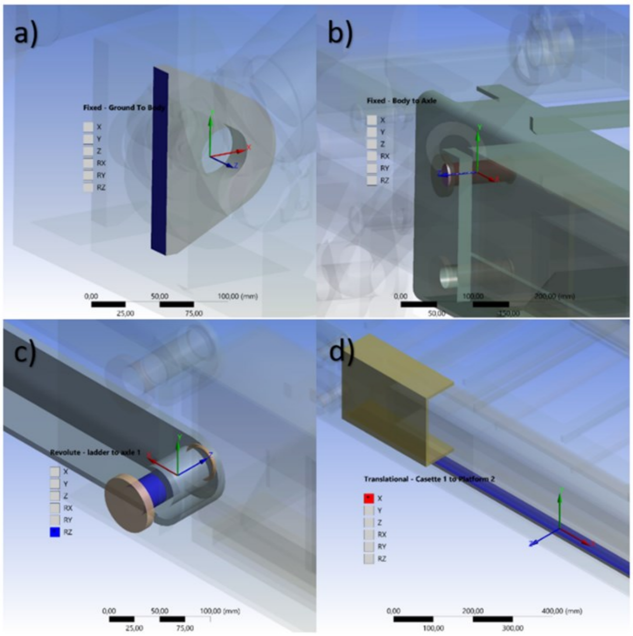

Figure 5.10 (a) Ground-to-body fixed, (b) body-to-body fixed, (c) revolute and (d) translational joints

A fixed joint is defined to parts as body-body and body-ground relation and constrained the motion for all DOFs (UX, UY, UX, ROTX, ROTY, ROTY). For instance, the face of the welded part is selected as the mobile body shown in Figure 5.10-a, then the body-to-ground fixed joint is assigned from the connections context tab. In Figure 5.10-b, the outer center face of the pin and inner face of the platform's hole are selected as mobile and reference bodies respectively to define body-to-body fixed joint.

A revolute joint is used for cylindrical parts and constrained 5 DOF as UX, UY, UX, ROTX, ROTY, and allow to move only rotation on the z-axis (ROTZ). A translational joint is used for linear sliding bodies and constrained DOF as UY, UZ, ROTX, ROTY, ROTZ, and enable to move only along the x-axis (UX).

For example, to define the revolute joint, the outer surface of the pin and center hole face of the ladder's bushing is selected as mobile and reference bodies in Figure 5.10-c, respectively; their coincident z-axis is aligned by orientating coordinate systems. Then, in Figure 5.10-d, the coincident surface of the first cassette and linear bushing plate of the platform are selected mobile and reference bodies, respectively, and the joint is defined as translational to allow linear motion. The same procedure is followed for each body carefully to set the single DOF of the assembly systems for every three mechanisms (opening mechanism I and II, and lifting/lowering mechanism).

5.2.3. Model Constraints and Solution

In this section, analysis settings, initial conditions, and loads are defined. The explicit time integration method is implemented in the transient dynamic analyses because the assembly model includes only rigid bodies, and the strain or stress results are not needed. Explicit analysis is used to solve the dynamic equilibrium of the gangway system at each different time step. In contrast to the implicit solver, the solution is not found with converged iterations for current and later time states. Thus, the response of the multi-part assembly can be solved efficiently and rapidly. Consequently, the time steps are set up by the number of steps, step end time, and time step choice under step controls. To apply a kinematic driving state to the single DOF mechanisms, joint loads are applied to the translation joints of the actuators as constant velocity. No person walks or stands on the gangway during the working period due to the safety rules. Therefore, only the inertial loads are applied. Finally, the solver control options are selected, and the Fourth-Order Runge-Kutta time integration method is used.

After the model is solved, the results are exported and analyzed in Matlab to plot and validate the obtained analytical solutions.

5.2.4. Validated Kinematic Results

The obtained analytical results (indicated in Figure 5.2, 5.3, 5.5, 5.7) are validated respectively by the ANSYS results, as shown in Figure 5.11. The ANSYS results are shown with circle markers, the solid lines represent the analytical results. As shown, position analyses results obtained using the analytical approach and ANSYS are in excellent agreement.

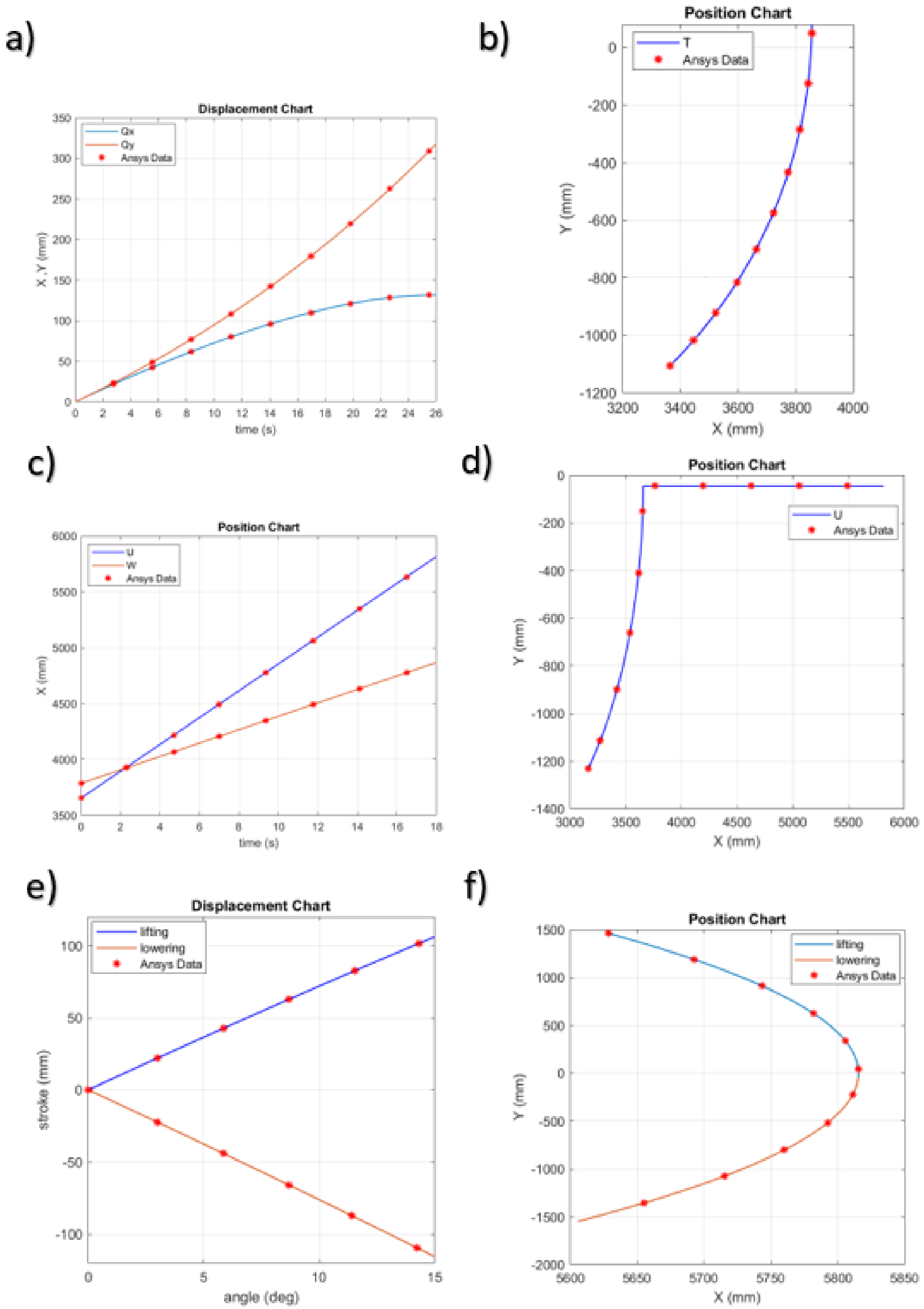

Figure 5.11 (a) Displacement of point Q and (b) position of point T in opening motion I; (c) positions of points U and W in opening motion II; (d) position of point U in opening motion I and II; (e) angular displacement of gangway and displacement of actuator, and (f) position of point U in gangway lifting/lowering motion

5.2.5. Force Results

Using the assigned material properties, force analysis can be performed. For instance, the force required to perform the opening mechanism I for hydraulic cylinder-1 is plotted in Figure 5.12-a. The force varies throughout the motion since the moment of the dynamic bodies and the angle of the actuator to horizontal axis changes. Considering whole motion range, the maximum force that the hydraulic cylinder needs to apply is obtained as 24.25 kN.

Similarly, the required force to push the cassettes on the platform by hydraulic cylinder-2 in the cable drive mechanism is found to be a constant force, 1.49 kN, that depends on the weights of the cassettes and friction (that is taken as constant in the analysis).

Finally, the force required to lift or lower the gangway for hydraulic cylinder-3 as a function of time is shown in Figure 5.12-b. The force varies when the hydraulic cylinder is extending and retracting since the moment of the dynamic bodies and the angle of the actuator with the horizontal axis is not constant during the motion. The maximum force is calculated as 24.56 kN.

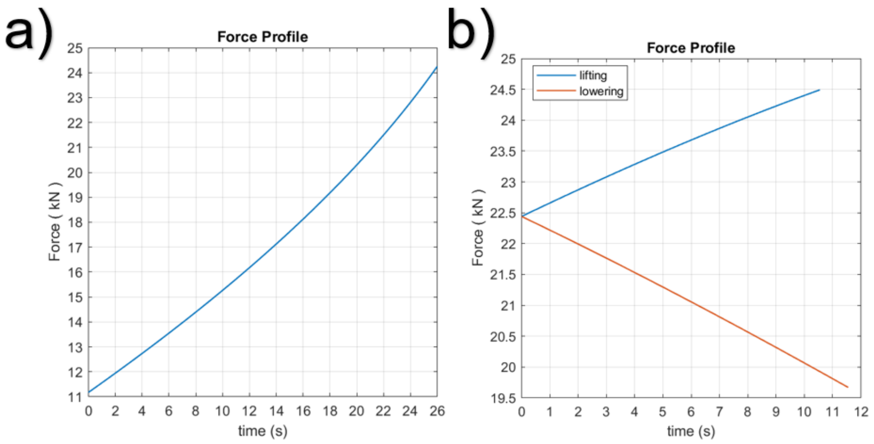

Figure 5.12 Force profile of the hydraulic cylinders 1 and 3

Based on the position and force analyses, the force profile, stroke width, maximum and minimum lengths of the hydraulic cylinders are found and an appropriate piston selection (Bosch Rexroth - Mill Type) is performed accordingly.

In the next step, the static structural analysis will be done to determine the critical sections and assess that the presented design will not fail during operation (and according to the guidelines [12]).

6. STATIC ANALYSIS OF THE GANGWAY

The structural analysis is widely used throughout many industrial areas such as aerospace, robotics, vehicle, construction, machinery, and shipbuilding industries to assess the critical sections in the design, and determine the safety factor of the system, the maximum load the part can stand, and the deflection of the structure. Therefore, to determine the safety of the constructed design, static structural analysis is performed under the loads specified by the guidelines [12].

The design of the multifunctional gangway has been carried out by utilizing static analysis. Note that this process is an iterative process; in other words, the gangway design is modified to satisfy the design requirements. For instance, if the length of the links needs to be modified, the position and force analysis is also performed again until the design meets the criteria set by the Section 3.1 (design requirements). The analyses are carried out using ANSYS Static Structural analysis that can accurately solve the (complex) real-life engineering problems robustly.

The static structural analysis of the gangway assembly designed with SolidWorks is conducted to determine the displacements, stresses caused by the gravity and external loading, and thus, safety factors in the gangway using ANSYS Workbench. Note that the maximum stress occurs in the full extension mode. Therefore, the full-extended gangway CAD data is exported to the ANSYS. The gangway assembly is symmetrical concerning the midplane. The XY-midplane is selected as a symmetry plane, and the full model is transformed into the half model by symmetry feature, as illustrated in Figure 6.1. Thus, the symmetric boundary condition improves computational efficiency by reducing the total number of nodes and elements.

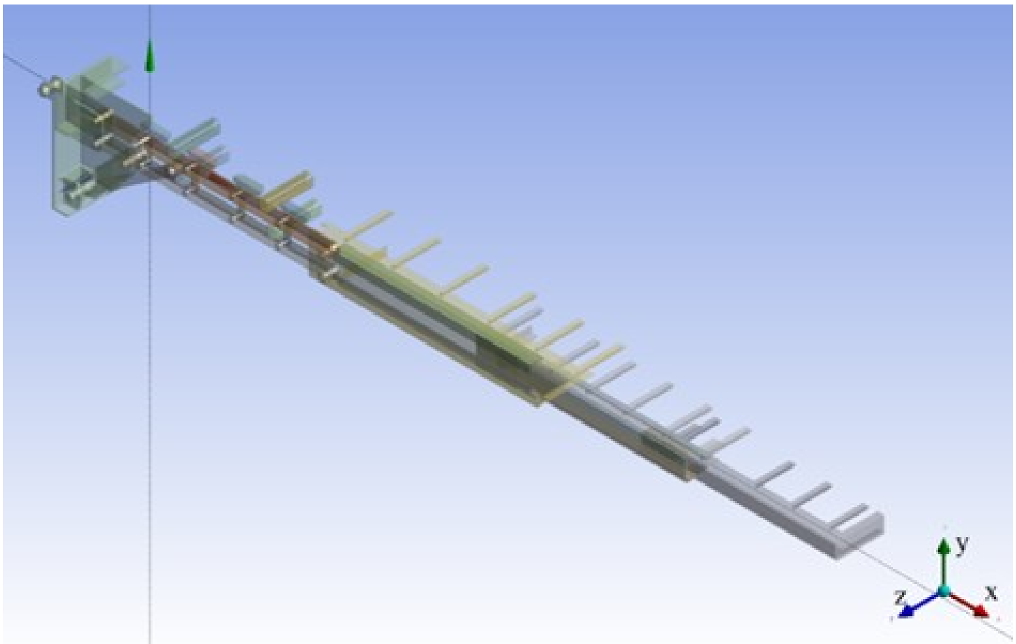

Figure 6.1 Half-geometry of the fully-extended gangway

Then, the defined materials (mentioned in Section 5.2.1) are assigned to bodies. The stiffness behavior of all assembly parts is designated as flexible automatically while it is selected rigid in the kinematic analysis. The contact regions are created automatically, and connections are defined between the bodies. The next step is the meshing process.

The discretization of the geometry is required to solve the mathematical model. The meshing tool divides the geometry into finite elements. The nodes on the structure are linked by lines. They form the mesh structure of the complex geometry. The differential equations are solved numerically by the finite element method. Finally, the mesh model of the gangway is obtained, as shown in Figure 6.2, and it contains 1602153 nodes and 709767 elements (see Section 6.1 for the details of the convergence analysis and the selection of number of elements in the analysis). On the other hand, mesh density is an essential factor in getting an accurate result that mesh converge process for obtaining finer mesh will be explained in the following section.

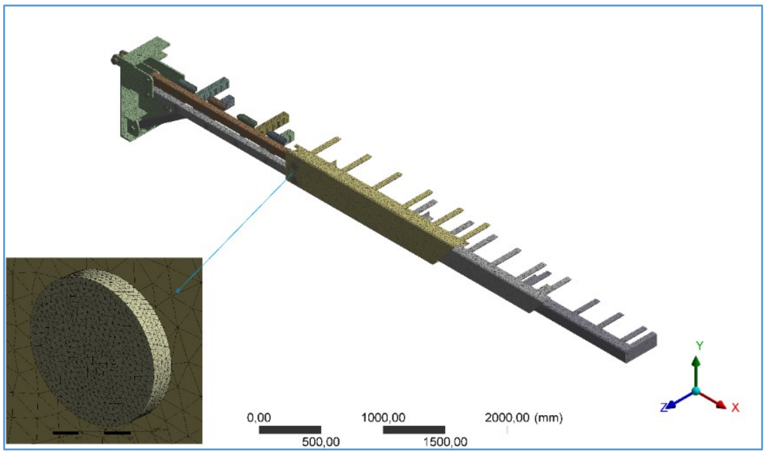

Figure 6.2 The fine mesh model of the gangway

In the setup section, supports and loads are defined. At this point, there are two possible conditions, such as cantilever and simply supported gangway. However, the boundary conditions and loads are applied according to the worst case scenario to meet design requirements. It is noted that the safety factor of the structure should be greater than 1.5 when one person (120 kg) is on the gangway; besides, the structure should have 350 kg carriage capacity considering 1.1 safety factor in an emergency according to design requirements. The maximum stress occurs in cantilever condition when load is at the tip of the gangway; therefore, the gangway is designed for this situation.

Moreover, the static analysis is conducted for the simply supported condition because the tip of the gangway is contacted via rollers with the port generally for passage. For both conditions, the welded faces of the gangway to the boat are described as fixed support. While applying loads, the half weight of the mass should be applied as a force due to the symmetrical boundary condition. For this reason, 588.6 N force is applied to the tip of the cantilever gangway. Then, the model is solved, and stress and deformation results are obtained, as shown in Figure 6.3.

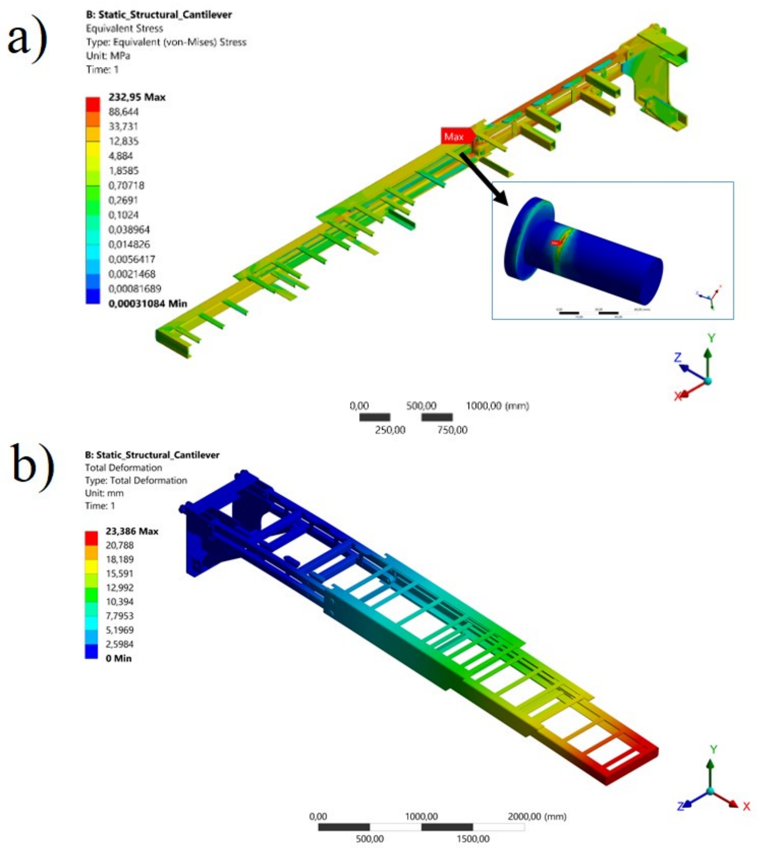

Figure 6.3 (a) Stress and (b) deformation distributions of the gangway

The stress distribution is illustrated in Figure 6.3-a in the logarithmic scale in half geometry for better appearance, and the maximum von Mises stress is obtained as 232.95 MPa in the platform body of the gangway. The maximum deflection of the gangway is found as 23.4 mm at the tip of the gangway. The safety factor based on von Mises criterion for cantilever gangway can be calculated with formula as given:

$$\text{Safety Factor} = \frac{\sigma_{yield}}{\sigma_{\max von-Mises}} \tag{6.1}$$

The yield strength of the 1.4404 Stainless Steel is 400 MPa (see Table 5.1), and the maximum equivalent stress (von Mises) is 232.95 MPa. Therefore, the safety factor is calculated as 1.717 and exceeds the limit safety factor of 1.5. Furthermore, the analysis is iterated for 350 kg mass load and safety factor is found as 1.138. As a result, it is capable of withstanding 350 kg load in emergency usage.

However, the static analysis is conducted for standard usage of the gangway. For this, simply support boundary condition is applied to the end of the gangway by constraining movement in the vertical (y-axis). On the other hand, the maximum stress could not occur when the load at the middle due to the non-uniform gangway geometry. Therefore, there is a need to determine the load location. Finally, this point is found 148.9 mm behind the mid-point by using iterative solution via variable load coordinates. Firstly, one-person weight is applied, and the maximum stress and deflection are obtained as 144.38 MPa and 1.78 mm, respectively. At this point, the safety factor of the gangway is found as 2.77, according to Eq. (6.1). Besides, it has 450 kg load capacity while the safety factor is 1.5 according to design requirements. Finally, the maximum mass capacity of the simply supported gangway is found as 710 kg considering 1.1 safety factor.

6.1. Mesh converge

In the finite element analysis, mesh converge is an important factor that affects the simulation accuracy. As the number of elements are increased, the results should converge. Therefore, several iterations that have been conducted in the analysis by increasing the element number *(using automatic global mesh controls in ANSYS sizing tab menu, the edge length is decreased proportionally (4.3 mm to 2.4 mm) by setting the range of the resolution values (0 to 6) to fine mesh distribution, respectively)* until the equivalent stress variation ratio of the assembly between two consecutive simulations is found to be under 1%, as listed in Table 6.1.

Table 6.1 Mesh refinement and converged von Mises stress values

Iteration	Mesh Nodes	Mesh Elements	Stress Value (MPa)
1	296550	118427	196.53
2	443973	178032	213.46
3	547993	227473	227.02
4	720244	303895	222.09
5	1008737	437449	229.57
6	1370268	599196	231.73
7	1602153	709767	232.95

Mesh distribution of the model is refined from coarse to finer models. The initial coarse mesh nodes, elements, and stress values were 296550, 118427, and 196.53 MPa, respectively. The finest mesh includes 1602153 nodes and 709767 elements, which about 5.4 and 6 times, respectively, relative to initial values. Finally, the actual von Mises stress value of 232.95 MPa is obtained with the least numerical error compared to the first iteration stress value of the 196.53 MPa. The maximum equivalent stress value of the assembly is acquired with a 0.052 % variation rate relative to the previous value (see Figure 6.4).

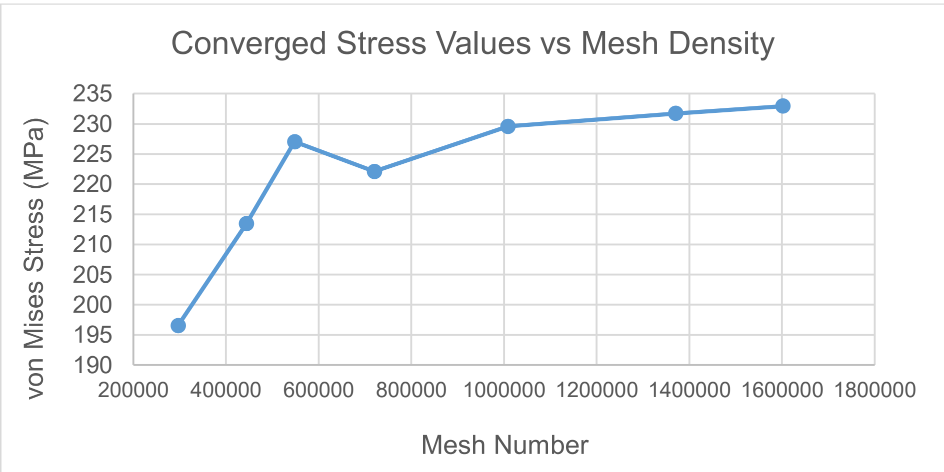

Figure 6.4 Convergence of the stress values with different mesh number

7. MANUFACTURING OF THE GANGWAY

After the design requirements have been met as mentioned in previous sections, the manufacturing process of the gangway is initiated. In Section 3, the design of the gangway has been conducted regarding the manufacturing processes. Therefore, in this section, the general manufacturing processes will be summarised.

All sheet metal parts of the gangway are fabricated from steel plates with a laser cutting machine. The main body part of the gangway is formed with these steel parts by welding. The ladder section of the gangway is fabricated from rectangular-cross section beams. The holes on the beams are cut by a drilling machine. The bushings and pins are machined by turning operations. The key slots and holes on the pins are machined by a milling operation. Then, pins and bushings are assembled into the holes, and steps of the ladder are attached, as shown in Figure 7.1-a.

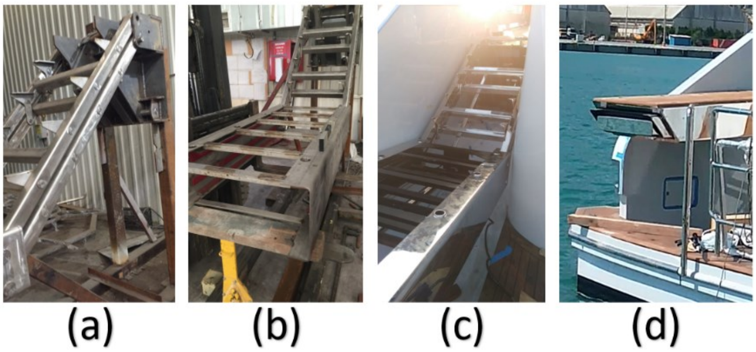

Figure 7.1 Manufacturing stages of the gangway

The sheet plates of the telescopic parts, such as platform and cassettes, are formed to obtain U-cross sectional shapes in bending machines. Then, box-shaped parts are formed with these parts and beams through welding (Figure 7.1-b). Cast polyamide rectangular cross-sectional beams are fastened inside the telescopic parts with bolts for telescopic sliding mechanism. Steel pulleys produced with a lathe are attached inside the cassettes, and steel wires are assembled to them for the cable drive mechanism.

Before attaching gangway to the boat, assembly of the gangway is completed and hydraulic cylinders are attached to the system to test the operation of the gangway. After stainless steel parts are polished, and other parts are painted, the gangway is assembled to the boat, as shown in Figure 7.1-c. Finally, the teakwood plates are fastened to the gangway (Figure 7.1-d); thus, the first design of the new multifunctional gangway has been implemented.

8. CONCLUSION

The focus of this thesis was to develop a *multifunctional gangway* model for increasing stacking efficiency and functionality of presently used internally mounted gangways in superyachts. It was achieved that the gangway turns into the ladder if not used, and enable a smooth walkway in use by parallelogram mechanism. Besides, with the hydraulic systems, position and orientation of the telescopic gangway can be controlled.

Throughout the gangway design, the relative safety rules [12] and the design requirements of the superyacht's builder company [11] were taken into consideration. As a start to the gangway model, a conceptual design was initially conducted to simplify mechanisms with rigid body linkages as schematics. This may be considered a basic process of the development to express the gangway parts as rigid linkages; and the length of the links, the distance between them and their angles as variables. Based on that model, kinematic analysis with an analytical approach was conducted and the governing equation of motions was solved by MATLAB in the analysis to determine the dimensions and locations of the gangway parts. Thus, obtained results have provided a basis of trial and selection of necessary design parameters to meet the design requirements.

Furthermore, the detailed working principle of all mechanism based on the developed model were explained: *(i) opening mechanisms I* and *(ii) II*, and *(iii) lifting/lowering mechanism*. In addition, DOF of all mechanism were calculated in accordance with Grübler and Kutzbach Equations. This is an important finding in determining the number of hydraulic cylinders. To sum up, firstly, the opening mechanism I provides the transformation of gangway from the ladder at the initial position to a smooth walkway with a parallelogram four-bar mechanism. As a consequence, the gangway has gained new functionality. Secondly, the opening II mechanism provides the extension of the gangway with the cable drive mechanism for less than one minute. Thus, using extra actuators for each stage of the telescopic gangway to drive all cassettes has prevented, and the cost and weight of the system are reduced. Finally, in the lifting/lowering mechanism, the inclination of the gangway is sustained to eliminate height difference between gangway and pier. Besides, the tidal effects, which might cause the gangway to crush into the pier during the rising/falling period of the sea, are minimized by lifting gangway a little bit higher compared to the level of the pier when the gangway is not in use.

The kinematic analysis results had led to valuable conclusions for the 3D design parameters. From the perspective of multi-body dynamics modeling of the gangway, a commercial computer-aided design (CAD) program as SolidWorks was utilized. The mechanical systems were simulated and checked with the assembly toolbar by defining connections between gangway parts. Besides, the manufacturing process was taken into consideration in the design stage to optimize production time and cost of gangway parts. Due to the weight limitations of yachts to ensure balance, the weight of the gangway was arranged not to exceed one-ton. Besides, the walkway width, the handrail height, the distance between handrail legs, and the height difference between steps were set to 0.6, 1.4, 0.5, and 0.24 meters to enable the safe transfer, respectively. Finally, the height and width of gangway boundaries were set 1.5 and 0.85 meters to proper housing of the boat space.

Then, the static analysis of the gangway was implemented with finite-element-method (FEM) using ANSYS Workbench (Static Structural toolbar) software. The developed first 3D design was applied in the static analysis to gain insight into the safety of systems. In the light of obtained analysis results also including kinematic analysis, the final design of the gangway was achieved which met all requirements of safety guidelines and design by modifying the gangway model. In conclusion, the gangway in cantilever position has one-person and 350 kg load capacity in normal working and emergency conditions, respectively. Besides, in the simply supported position, in other words, when the tip of the gangway is contact with landing point, it has 450 kg and 710 kg load capacity in normal and emergency usage.

The gangway system was designed to be actuated with hydraulic cylinders. In the kinematic analysis, the hydraulic cylinder was expressed as a driving link and the dimensions of them were obtained from the analytical approach. Due to the difficulties in accurately calculating the driving forces in the complex assemblies, the ANSYS Workbench (Rigid Body Dynamics toolbar) was used to determine the required forces of each hydraulic cylinders. For this purpose, the constructed gangway model was exported to ANSYS, and imperative kinematic constraints were defined with joints among rigid bodies. Then, first, the position analysis was performed and the motion of mechanisms was simulated to validate the analytical model. The obtained results are precisely consistent with analytical results. It was concluded that the maximum operational length and angle of the gangway were 5.81 meters and ±15 degrees. Besides, the minimum horizontal distance of gangway in full extension mode (i.e. the x-distance of the gangway in maximum operational length when the rotation angle of it to horizontal was -15^{o}) was set to 5.6 meters due to preventing a gap which may occur in mooring position between boat and dock. Secondly, force analysis was conducted to determine the actuator forces during the motion of the gangway mechanism. Consequently, the findings obtained in the analyses such as the force profile, stroke width, maximum and minimum lengths of hydraulic cylinders enabled the appropriate selection of pistons.

Water corrosion is a substantial criterion for material selection in marine applications. Accordingly, stainless steel was used in gangway design due to its high mechanical properties and polishability, ensuring aesthetic appearance in addition to its corrosion-resistance. However, composite material is at a present time generally accepted in marine structures because of its considerable potential as an alternative for traditional metals due to its light weight, high strength, corrosion resistance, and flexibility (i.e., applicable for manufacturing complicated shapes with easy molding techniques), meaning that future work utilizing composite material might be a fruitful research path going forward. It is important to highlight the main objective of this study that it aims to develop a gangway mechanism and design to improve stacking efficiency and functionality. This assessment might be addressed in future studies that optimized standard gangway design with carbon prepregs and optimization of the composite material system can be achieved.

At last, the stainless steel gangway was manufactured and hydraulic systems were integrated to test the operations of the gangway. After all tests and certification procedures conducted by the shipbuilder, the gangway was applied to the superyacht. In conclusion, ***(i)*** the developed parallelogram gangway mechanism has gained a functionality to the gangway as a ladder in the unused period, ***(ii)*** stacking efficiency of gangway ensuring longer walkway is increased due to the maintaining of retracting mechanism and telescopic systems on the platform, ***(iii)*** longer gangway is achieved sustaining the extension of telescopic system by locating at the end of the ladder, and ***(iv)*** this mounting solution has enabled the application of the internally mounted type of gangway in space-limited yachts.

9. BIBLIOGRAPHY

[1] International Chamber of Shipping, “Annual Review 2019,” Author, London, 2019.

[2] United Nations Conferance on Trade and Development, “The Review of Maritime Transport 2018,” Author, Switzerland, 2018.

[3] International Chamber of Shipping, “Annual Review 2017,” Author, London, 2017.

[4] S. K. Ribeiro, M. J. Figueroa, F. Creutzig, C. Dubeux, J. Hupe and S. Kobayashi, "Chapter 9 - Energy End-Use: Transport," in *Global Energy Assessment - Toward a Sustainable Future*, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, Cambridge University, 2012, pp. 575-648.

[5] T.C. Ulaştırma ve Altyapı Bakanlığı, “Ulaşan ve Erişen Türkiye 2018,” Author, Ankara, 2018.

[6] R. a. R. C. Anderson, A Short History of the Sailing Ship, New York: Dover Publications, 2003.

[7] "A Summary of Yachting History," *The Lotus Magazine,* vol. 5, no. 8, p. 505–512, 1914.

[8] J. E. Vance, "Encyclopaedia Britannica," Encyclopaedia Britannica, Inc., 22 June 2018. [Online]. Available: https://www.britannica.com/technology/ship. [Accessed 30 December 2019].

[9] R. M. Steward, Boatbuilding Manual, 2nd ed., Camden: International Marine Publishing Company, 1980.

[10] T.C. Ekonomi Bakanlığı, "Gemi İnşa Sektörü," 2016. [Online]. Available: https://ticaret.gov.tr/data/5b87000813b8761450e18d7b/Gemi_İnsa_Sanayi.pdf. [Accessed 31 December 2019].

[11] *Kando 110.* [Art]. Ava Yachts Co. Ltd., 2019.

[12] DNV GL, "Certification of offshore gangways for personnel transfer," DNV GL AS 2020, 2015.

[13] İ. Genç, "Designing and Analysis Phases of Four Elements (Master's Thesis)," Atatürk University, 2007.

[14] Besenzoni SpA, "Yacht Gangway," [Online]. Available: https://www.nauticexpo.com/prod/besenzoni-spa/product-21536-285492.html. [Accessed 30 12 2019].

[15] M. Grimaldi, "Manual gangway for a boat". United States Patent 0,050,045 A1, 26 February 2009.

[16] G. Besenzoni, "Telescopic gangway for boats with a simplified construction". United States Patent 6,748,895 B2, 15 June 2014.

[17] P. Sacco, "A movable gangway for a boat, having a rotating actuator". WIPO (PCT) Patent WO2010013271A1, 4 February 2010.

[18] G. Franceschi, A. Borzoni, M. Maracci, G. Besenzoni and G. Besenzoni, "Access gangway for boats made of titanium". European Patent 1,902,940 A3, 21 May 2014.

[19] D. E. Yunus, "Design and Manufacturing of Carbon-Fiber-Reinforced Polymer Composite Gangway (Master's Thesis)," Ege University, 2011.

[20] R. Rohden, "Ship and gangway for the same". United States Patent 8,950,353 B2, 10 February 2015.

[21] G. D. Hone, G. O. West and E. P. Beaz, "Gangway system". United States Patent 6,330,726 B1, 18 December 2001.

[22] F. Worpenberg and L. Scharf, "Telescopic gangway". United States Patent 6,496,996 B1, 24 December 2002.

[23] B. Bonet, “Gangway for Embarking and Disembarking Passengers”. United States Patent 0,247,310 A1, September 26 2013.

[24] R. K. N. J. Prins, "A Vessel, Provided With A Gang Plank For Coupling To An Offshore Pole". European Patent 1,315,651 B1, 14 March 2002.

[25] W. F. Prins, “Gangway construction having a guiding assembly with pulley wheels and guiding cables”. United States Patent 8,745,801 B2, 10 June 2014.

[26] C. A. Fleischer, M. Kapelanczyk and G. W. Klein, “Rotating gangway support platform”. United States Patent 7,996,942 B2, 16 August 2011.

[27] M. J. Watchorn and A. J. Eaton, "Gangway apparatus". United States Patent 8,127,388 B2, 6 March 2012.

[28] J. C. Brignola and D. Dumont, “Ship with a telescopic gangway for transferring individuals between the ship and a stationary or near-stationary object at sea, such as a wind turbine”. European Patent 3,247,623 A1, 29 November 2017.

[29] R. E. Wilson, "Variable length catwalk". United States Patent 3,245,101, 12 April 1966.

[30] O. G. Maxson and M. L. Peterson, "Personnel transfer gangway". United States Patent 4,011,615, 15 March 1977.

[31] T. Sugita, "Gangway ladder arrangement". United States Patent 4,335,803, 22 June 1982.

[32] J. J. Mampaey, “Gangway construction”. United States Patent 3,875,603, 8 April 1975.

[33] G. S. Edge, "Gangway system". United States Patent 4,035,861, 19 July 1977.

[34] B. H. Gonzalez, “Gangway ladder”. United States Patent 3,970,169, 10 July 1976.

[35] S. M. Lippka and C. R. Peterson, “Self-adjusting variable height gangway system”. United States Patent 4,998,313, 12 March 1991.

[36] J. Patrick J. Ricci, "Portable gangway with leveling stairs". United States Patent 5,794,292, 18 August 1998.

[37] M. Spina, “Moving gangway for boats with vertical movement”. European Patent 1,719,696 A1, 8 November 2006.

[38] J. K. Cooley and K. P. Cooley, “Enhanced adjustable gangway”. United States Patent 8,387,192 B1, 5 March 2013.

[39] S. Leske, “Device for the safe transfer of personnel or material from an object configured as a boat to an object moving relative thereto, and boat comprising the device”. United States Patent 0,038,691 A1, 17 February 2011.

[40] B. Nøstvold, “Gangway for transferring personnel and equipment from a first device to a second device”. United States Patent US 10,486,775 B2, 26 November 2019.

[41] R. W. Honeycutt, “Gangway bearing retainer plate”. United States Patent 8,387,191 B2, 5 March 2013.

[42] S. C. Mizell and A. J. Cook, “Automatic locking device for track mounted gangway”. United States Patent 8.479,884 B2, 9 July 2013.

[43] J. R. Lawson and I. James Pearce Daniel, "Gangway having position locking assembly". United States Patent 10,253,464 B2, 9 April 2019.

[44] J. W. Reichert and J. D. Scott, “Gangway having hydraulic position locking assembly”. United States Patent 10,145,070 B2, 4 December 2018.

[45] D. J. C. Salzmann, "Development of the Access System for Offshore Wind Turbines (PhD Thesis)," Delft University of Technology, 2010.

[46] F. Yu, *Modeling, Simulation and Control of Motion Compensated Gangway in Offshore Operations (Master's degree),* Norwegian university of science and technology, 2017.

[47] L. Liang, Z. Le, S. Zhang and J. Li, "Modeling and controller design of an active motion compensated gangway based on inverse dynamics in joint space," *Ocean Engineering,* vol. 197, 2020.

[48] P. Merriaux, R. Boutteau, P. Vasseur and X. Savatier, "IMU/LIDAR based positioning of a gangway for maintenance operations on wind farms," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, Chicago, 2014.

[49] P. Stuberg and C. J. Amundsen, "Optimized Offshore Gangway Operations on Monohull," in *MTS Dynamic Positiining Conference*, Houston, 2015.

[50] W. Huang, B. Li, X. Chen and R. Araujo, "Numerical and experimental studies on dynamic gangway response between monohull flotel and FPSO in non-parallel side-by-side configuration," *Ocean Engineering,* vol. 149, pp. 341-357, 2018.

[51] Q. Dong, H. Lu, J. Yang and X. Guo, "Dynamic gangway responses between TLP and semi-submersible platform during tender-assisted drilling," *Marine Structures,* vol. 67, 2019.

[52] Y. C. Chung, *Dynamic Analysis of the Ampelmann G25 Gangway (Master's Thesis),* Delft University of Technology, 2016.