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Parametric Mechanical Design for Systems Integration and Simulation of Virtual Crane

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Abstract

Efficient, flexible performance, operational safety, environmental issues and cost targets are became more and more urgent in the crane design system. Thus, a virtual crane prototyping (VCP) system consisting of various sub-systems, such as mechanical part, could be a feasible tool to evaluate multiple design concepts and conduct the trainings with a short time period. In this project, we focus on how to do a virtual prototyping for mechanical part of the marine crane. We aim to develop a library that is a scripting-based and could able to generate a model for 3D visualization and simulation in VCP framework. To establish a library, we separate the crane into components in a parametric way. The virtual crane assembled with the library could be easy to customization and changed its parameters according to the following simulation's requirements.

Combined parametric design methods in other research fields such as automobile and aviation; we will develop a parametric design method for modelling marine crane. We focus on the crane's overall operation and those are related with the statics, kinematics mathematics expressions of the crane; based on those expressions we can find the parameters which are basic and independent in the system; use those parameters to create 3D mesh models used for different purpose.

Parametric mechanical design for systems Integration and simulation of virtual crane offers a novel solution to expend the universe for exploration of design instances for virtual prototyping, in particular as a model for generating parametric designs.

Preface

The objective of this work is to develop a parametric design method for marine crane design, which will be help for developing a new platform for product development and virtual prototyping in the maritime industry. Combined parametric design methods in other research fields and the theories of mechanical design, from the statics, kinematics mathematics expressions of the crane we can start work and get a feasible alternative.

I would like to thank my responsible advisor at NTNU in Aalesund, Professor Houxiang Zhang and research assistant Yuxiang Deng for valuable input, discussions, help and guidance throughout the work of this thesis.

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TERMINOLOGY

Symbols

${}_{B}^{A}\mathrm{T}$	Homogeneous transformation matrix
${}_{B}^{A}R$	Rotation matrix
${}^{A}\mathrm{P}_{Borg}$	Position vector
$f_{1\times 3}$	Perspective transformation
J	Jacobians matrix
v	Velocity
$\dot{\theta}$	Joint velocity
F	Force
τ	Torque

Abbreviations

VCP	Visual Crane Prototyping system
ROV	Remotely Operated underwater Vehicle
3D	3 Dimensional
CAD	Computer Aided Design
CAE	Computer Aided Engineering
IDDL	Integrated Data Description Language
IIICAD	Intelligent Integrated and Interactive Computer Aided Design
PIGMOD	Parametric and Interactive Geometric Modeller for mechanical Design
PLM	Product Life Management

1 Introduction

1.1 Project background

Maritime cranes are widely used as an important subsystem to handle and transfer objects from large container ships to smaller lighters or to harbour quays. Crane operation is always a challenging task which involves many problems such as load sway, positioning accuracy, suppression, collision avoidance, and manipulation security. Traditional maritime cranes, which are relatively big, heavy and stiff, rely on complex kinematic models of their system as well as an equally complex model of the environment with which they interact. However, the current crane designing process is still carried out in a traditional way, which lags behind the urgent, fast and dynamic requirements, which change frequently. When considering both working efficiency and operation safety, the on-going crane design is far from good. As a result, the maritime cranes are designed heavier, stronger and bigger than necessary in order to be sure that the requirements regarding working space, payload capability, operational efficiency and redundancy, and manipulation security, are met.

With the development of technology, safer crane operations are promoted through engineering design and crew training on system and operational simulators. Current crane design and production lead-times are constantly decreasing, and mistakes or system malfunctions may cause fatal accidents, project delays and costs overruns. Efficient, flexible performance, operational safety, environmental issues and cost targets are became more and more urgent in the crane design system. As a result, simulators are based on mathematical models of the real systems involved, and a major challenge is to be able to develop and configure realistic models within short time frames. Evaluating multiple design concepts can be done effectively using simulation tools, where trade-offs and many alternatives can be evaluated within a short time period.

Thus, developing a virtual crane prototyping (VCP) system integrated engineering design, control theory and hydraulic performance in such a way as to allow the virtual prototyping environment to provide pre-testing, fault finding, error investigating, and operation verification functions. The results from the project will generate new opportunities for collaboration and allow for more efficient work processes, thus improving the technological level and productivity of the maritime industry. In this project, we focus on how to do a virtual prototyping for mechanical part of the VCP.

1.2 Problem and motivation

Currently marine operations are becoming more and more demanding. Heavy lifting and handling at depths of several thousand metres, precise installation of subsea modules weighing several hundred tons, platform support in the ice and the cold of the northern regions, etc., are all examples of new demanding marine operations. The complexity increases even further when taking into account the fact that these operations require a much greater coordination between professionals, for example during ship manoeuvring and crane, winch and ROV operations. The operational performance has to be considered in the designing phase. Traditional training simulators are related to the manoeuvring of ships at sea and in harbour [1] – that is, in calm water without effect of waves – or at a subsystem level to learn to use a special piece of equipment decoupled from the total system. The training simulator is an independent part and is separate from the design process. The solution to the integration of crane design and operation as a whole is not simple and as such, simple "one-plus-one-equals-two" kinds of methods will not work. There are still several gaps between the current simulation tools and the urgent industrial demands in crane design. The simulation tools for sub systems have different focuses, which make them special. Generally there aren't any software tools that take care of whole crane design process and operation performance together. There is a need for standardisation of what constitutes the components of a marine crane and their external interface in order to allow implemented models to be re-used in different simulation settings, be it design or training.

The virtual crane prototyping project will integrate the current technology and know-how, and it is expected to bring significant new scientific advances into the maritime industry. New solutions, design concepts and equipment combinations can be simulated and tested in a laboratory environment before being built. Such virtual prototypes will encourage rapid innovation, and they will help to bring design, training and operations closer together.

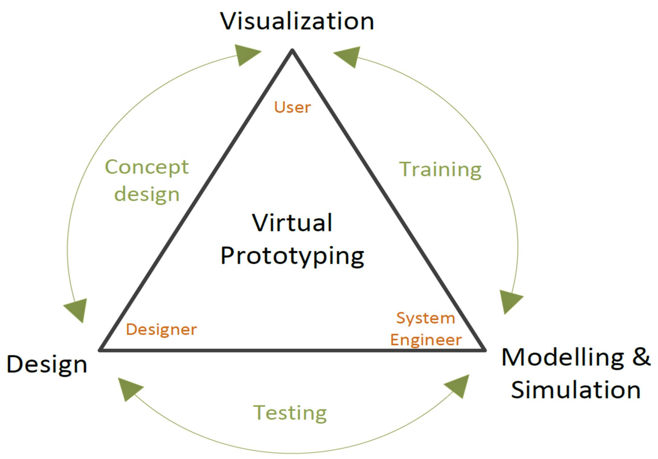


Figure 1.1 Virtual prototyping

The proposal of VCP brings the different parties together including the user, designers, system engineers and even marketing and after sales departments like the figure 1.1 showed. The mechanical part model is the base of the VCP. The mechanical part modelling is the most intuitive manifestation of the design scheme. Before modelling we will create a library contained generic models of all key maritime crane parts. With that part library a marine crane's prototype will be assembled in a short period. It will be showed to the user directly as a visual demonstration and according to the feedback each mechanical part model could be easily adjusted in geometric shapes and lengths with the users' requirements. That will be very efficient in doing the concept design for the designers. It also can be used for system testing combined with the control and hydraulic system like the figure 1.2 showed. The VCP includes performance parameter definitions, System performance, Operational safety and efficiency, System metrics (energy consumption, payload, system dynamics, system costs, etc.) The results from the project will generate new opportunities for collaboration and allow for more efficient work processes, thus improving the technological level and productivity of the maritime industry. Only after the mechanical model created, hydraulic part and control part could be added into then a complete VCP system will be finished. So mechanical part modelling provides an effective platform and it's the base of the VCP system.

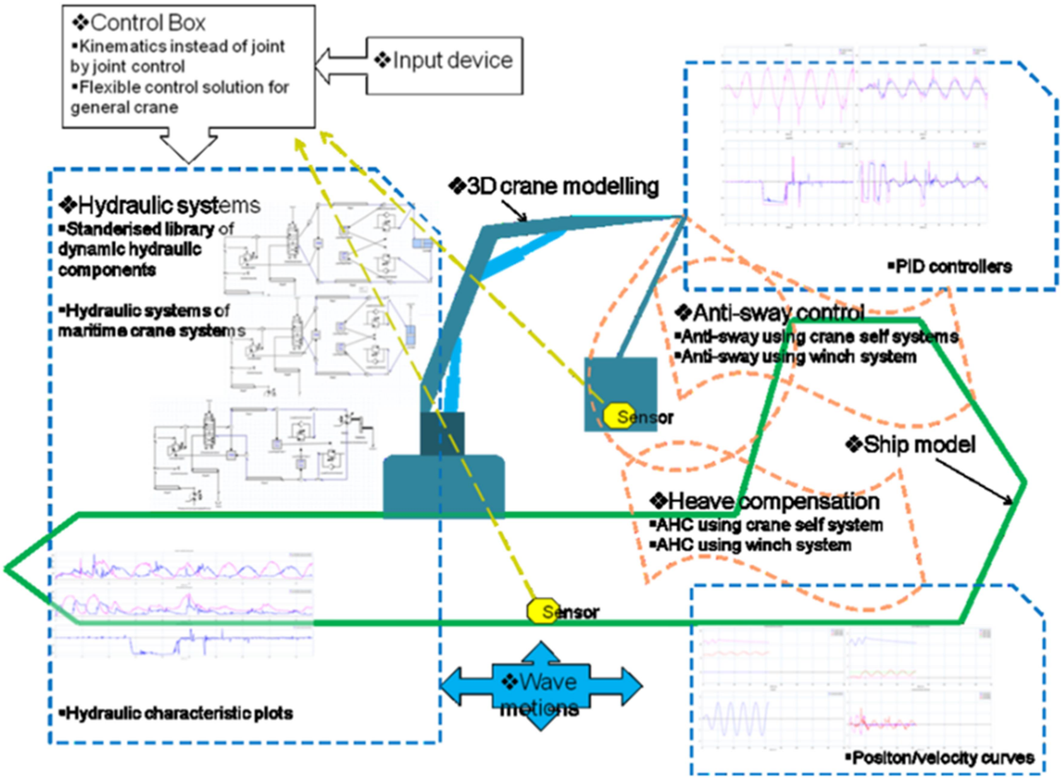


Figure 1.2 Marine crane design and control

Modelling for the mechanical part of the VCP is important for the designer in the stage of conceptual design. Decisions made at the conceptual design stage have significant influence on factors such as costs, performance, reliability, safety and environmental impact of a product. During that early phase of a product’s life cycle is usually imprecise, approximate or unknown. Conceptual design’s primary concern is the generation of physical solutions to meet the design specification. A study conducted by Lotter indicates that as much as 75% of the cost of a product is being committed during the design phase [2]. More importantly, a poorly conceived design concept can never be compensated for by a good detailed design.

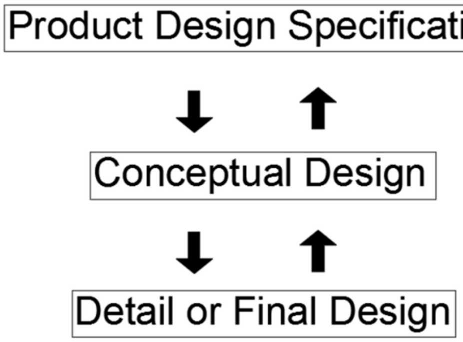


Figure 1.3 The phases of design

So modelling of mechanical part is the foundation for developing VCP and also useful for the conceptual design for the marine crane. We aim to develop a library that is a scripting-based and could able to generate a model for 3D visualization and simulation in VCP framework. Thus, a logical and theoretical way to outline the possibilities of such thinking for modelling a marine crane is fruitfully needed in this thesis. After researching, we use a parametric design method in VCP.

A rigid body model built by current available software tools contains too many mechanical properties including the geometry, the mass and inertia, constrain, and graphical properties for visualization, etc. The simplification process for simulation purposes can be tedious for presenting an initiative design concept. Many of these data must be obtained and transferred in many various ways and formats for later use. But in the concept design or simulations which are used to test the crane's operation we only need to consider the kinematics of the crane that means a crane model contained necessary dimension of each part of the crane is enough [3]. So we find a design method for VCP mechanical part modelling, parametric mechanical design, which can create and modify the model rapidly as well as making a model to evolve kinematics features. Hence, that leads to our research question:

- How to adjusting existed methods about parametric design in other research fields such as the aerospace and aircraft, and automobile industries to produce a method for modelling marine crane.
- Which parameters can be parameterized from the crane?
- How to formulate parameters library for adjusting and manipulating marine crane requirements into a model.

1.3 Current approaches

Virtual prototyping [4] is an innovative methodology of combining mechanical modelling and simulation to increase the efficiency of designing and prototyping embedded control systems and devices. It can connect software design and control algorithms to the 3D CAD mechanical models to test the mechanics of the system before building a low fidelity physical prototype. Currently, most of the virtual prototyping is built upon CAD/CAE software. Below are the benefits of CAD/CAE software:

- Gain greater understanding of a process
- Identify problem areas or bottlenecks in processes
- Evaluate effect of systems or process changes such as demand, resources, supply, and constraints
- Identify actions needed upstream or downstream relative to a given operation, organization, or activity to either improve or mitigate processes or events
- Evaluate impact of changes in policy prior to implementation

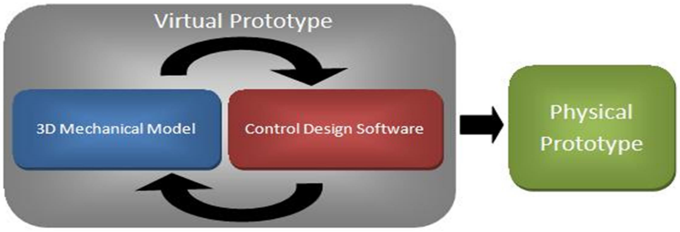


Figure 1.4 The working flow of prototype

Traditionally, process of utilising CAD/CAE is selecting construction equipment, reviewing constructability, and arranging construction methods and site layout. When a model is built, such mechanical system is logically based on mathematical model to find analytical solutions for reality problems. Solutions are enabling the prediction of the behaviour of the system from a set of parameters and initial conditions. Since there are four steps and the model is based on an understanding of mathematical issues, this approach needs a heavy project teams to handle large information and modelling elements [5]. Hence, it reduces possibilities of flexibility when requirements changes and minor adjustment are needed.

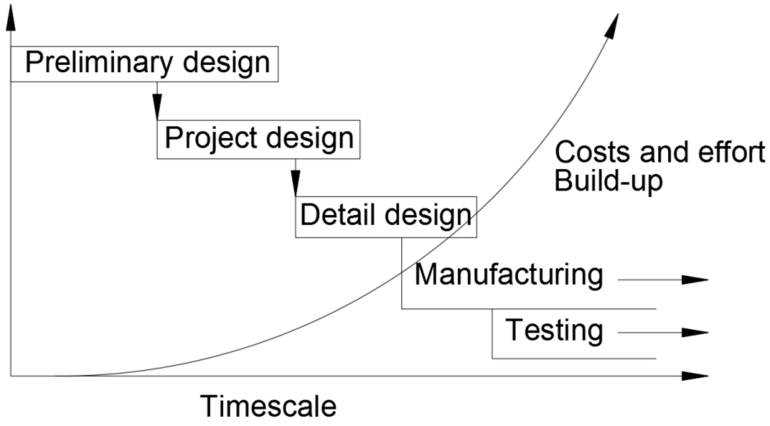


Figure 1.5 Traditional design processes

Mechanical designs need to consider material properties, tools selection, manufacturing, assembly processes, etc. Current CAD systems lack mechanisms for “amateur” participation in a design process. In current CAD systems, basic geometric information of a part such as geometric shape, dimensions, and features is specified by designers directly and explicitly. Thus, this is largely dependent on engineering knowledge of designers. For customers, they usually lack this knowledge. A CAD system that cannot follow customers’ intentions will not establish effective human-machine communication channels. Customers’ specifications tend to be ambiguous.

A group of researchers developed an IDDL (Integrated Data Description Language) to code design knowledge in the IIICAD (Intelligent, Integrated, and Interactive Computer-Aided Design) system. It uses the logic programming paradigm to express the design process for manipulating design objects, whereas the object oriented programming paradigm is used to express design objects. The PERSPECT system is a design tool that aims to support the effective utilization of experiential knowledge in numerical engineering design, in which design knowledge is generated by learning about their existing design domain (Domain Exploration) and “sharing” the learning activity between designers and computers (Shared Learning) so as to ensure the knowledge represented in computers is understandable to designers. CASECAD is a multimedia case-based design system that integrates traditional CAD and case-based reasoning. It stores and utilizes design cases in both textual and graphical modes. The main modules include case memory, case base manager, case-based reasoner, CAD package, and graphical user interface. The system IDEAL uses analogical reasoning to retrieve knowledge of a familiar problem or situation that is relevant to a given problem and transfers that knowledge to solve the current problem, which is cross-domain case-based reasoning. None of these systems are able to provide seamless transition from functionality to form.

CAD / CAE soft wares allow us to make some modifications a posteriori regarding these primitive entities in current CAD systems. However, this does not work for complex elements where we want relations to be maintained while modifying their parts independently. Variations in design are a fundamental part of the design process in the search for solutions to design problems. Design variations support improvement of design which in turn improves the quality of designed artefacts. Designers constantly go back and forth between different alternatives in the universe of possible solutions, working in a particular part at a given time, or looking back at the whole from a broader perspective. This is a continuous and iterative search process of variations of a design idea, and it is very likely to revisit a previously abandoned solution to rework it. As a result, designers demand flexible tools that allow variations in the design process until a solution is established for further development.

Parametric design is, in a sense, a rather restricted term; it implies the use of parameters to define a form when what is actually in play is the use of relations. Forms are created by combining basic entities that are inserted in the model after a basic template, which includes their “proper parameters”, is filled. A line, for example, is an entity that becomes part of a model once two parameters, its length and its direction, are specified. A polyline is a set of lines joined at their vertices whose position parameters must also be specified when it is created. A prismatic meshed volume is inserted in a model through four parameters, its location, length, width, and height. We can define a metal window as a block but if we change the scale at the moment of insertion, frame sections will change in the same proportion as the overall magnitude and we will not be able to keep a standard frame with different opening dimensions. But we can still define a procedure, through some programming language, in such a way that only the relations are specified and the adequate dimensions are defined only at the moment of insertion in the model. And, it is obviously of interest in the case of VCP due to the fact that a very important number of component elements of crane can be grouped in families that tend spontaneously to be parameterized. And, if this can be done in a satisfactory way, it can save a lot of time for the VCP and computer memory and will also help the management of these elements. To my knowledge, after investigating the related datum, there is no related work about parametric design of the marine crane.

In the following part, there will be three theories introduced. One is proposed how to split a system into units, one is introduced how to define those units and the last one is suggested how could use those unit assemble a new parametric model.

In [6], Sehyun Myung and Soonhung Han propose a concept of parametric design of assembly using functional features. Based on the concept of design unit to an engineering system design, designers modify design units when a system similar to existing one is to be designed. If a design unit is to be modified, the geometric shape or the function of the design unit should be modified. As showed in the figure 1.6 showed, design units can be subdivided into several levels as needed, and each design unit is mapped onto a physical assembly in the manufacturing space. Functional features near the bottom of the hierarchy of the design space correspond to machining features in the manufacturing space. It is not the one to one correspondence.

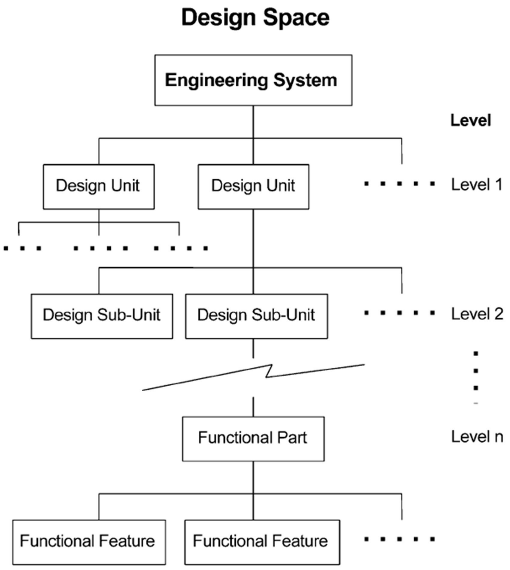


Figure 1.6 Hierarchy of design units and functional features in an engineering system

In [7], the authors thinks Relations in a feature based product model can be classified into two categories, geometric relations and non-geometric relations. Geometric relations refer to those constrained associations among topological or geometrical entities, i.e. solids, faces, edges, vertices, surfaces, curves, points, etc. Many publications focus on geometric relations in a feature model [8], such as relations are explicitly declared and represented as geometric constraints, which allows maintaining the geometric integrity of features. Unintentional feature interactions may affect validity of features [8]. These interactions usually cannot prevent via geometric or algebraic constraints. Nonetheless, such geometric feature interactions can only be managed through associations between a feature model and a geometric model. Non-geometric relations refer to any dependency associations involving entities representing non-geometric properties. For example, in process planning, the clamping faces or accessing faces are required to machine a feature. Interferences may occur if a wrong machining sequence is used [9]. Then the constraints applied to define interference checking entities are non-geometric relations. Taking another example, two features, which may not overlap spatially and even belong to different product life cycle stages, may interact with each other [10]. Such interactions defined are also non-geometric relations. In addition, non-geometric relations also exist between features and non-geometric entities. For example, at the design stage, functional-form matrixes, bipartite function-feature graphs, design flow chains, design key characteristics, and mapping hierarchies might useful for linking abstracted concept features to product functions [11, 12]. At the process planning stage, machining features are also related to non-geometric entities, such as machines, cutting tools, and machining processes [13, 14]. Currently, it is still a challenge of research to completely represent non-geometric relations and to validate product models using non-geometric relations. Connection features are used to represent the insertion position, insertion path, tolerances, contact area, etc. Assembly planning activities, such as fixture planning, feeding planning, stability analysis, etc., generates features. Kim et al. [15] studied the assemblies created by welding and riveting. They used the associations among form features, geometric constraints, and joining methods to represent engineering intent. Non-geometric information is included in features and used to check whether the design specification is satisfied by the selected joining methods, such as degree of freedom. These two feature definitions link engineering knowledge, non-geometric entities, features, and product geometry explicitly.

A new approach to parametric design, design procedures, is introduced in [16], offers designers a powerful way to quickly generate parametric models that they can use for design exploration. A Design Procedure is as a set of instructions that performs actions that generate parameterized geometrical models. Unlike traditional parametric models, where geometrical components are varied, a design procedure constructs a parametric model which can then be used to generate instances of designs, therefore changes and transformations of both topology and geometry are possible. The design procedure carries instructions in a systematic order, where geometrical components are constructed and parameterized at the same time. The design procedure creates a parent-child type dependency relation just like in any parametric model, where the parent is the input, and the resulting geometry is the child. The two point procedure for creating a line will have the end points of the line as parameters; while each of the points is a parametric entity on itself, therefore a design procedure results in a parametric model where input shapes can be parameterized entities creating a special kind of encapsulation

1.4 Problem formulation

The new marine cranes should be designed optimised with respect to operational performance rather than the performance of individual components and systems. Parametric design of virtual prototyping can meet the requirement. It decreases the risks associated with machine design by improving the understanding of customer requirements and speeding up the design process as well as streamlining debugging.

Traditional designing way is defined as:

1. Complicated. It refers to 2D drawings.
2. Changing the dimension of any part is time consuming.
3. Compatibility issues. It establishes a virtual prototype model based on CAD software, and then imports this prototype model into other simulation environment. That may cause by the compatibility between the CAD software and simulation software.
4. There is no interface for other systems such as hydraulic system.

The key point of the parametric mechanical design for virtual crane is separating the carne into several typical parameters. Those parameters or the combinations of the parameters should reflect on critical features of the real crane, like its volume and weight. If we want to change its frame, we only need to replace the part cross area's shape and the part's length.

To get the crane's parametric modelling, we should solve the following questions:

1. How many types of the marine cranes commonly used are there in the world?
2. What are the similarities and differences of those marine cranes and how to abstract and simplified those features in those cranes?
3. How to define the benchmark in each part and make it easier to mark the dimensions in each part?
4. Could those features are interdependent or could be merged?

1.5 Objectives

Primary objective: the project will address the development of a framework for overall crane’s mechanical part design, allowing flexible configuration of marine cranes and verification of operational performance as a part of the design process. Develop a parametric design method for marine crane mechanical part, which will be helpful for developing a new platform for product development and virtual prototyping in the maritime industry.

For the following 6 months timeframe, we have the following secondary objectives:

1. General investigation
    - Investigate the existing marine cranes
    - Investigate the relevant regulations
    - Investigate the 3D modelling tools
2. Crane simplification and parameterization
    - Simplify the most commonly used maritime cranes
    - Classify the components from different types of cranes into proper categories and establish the library architecture
    - Identify the key parameters defining each component
    - Define the joints in common cranes
3. Develop mesh model generator
    - Identify further parameters of each component which are required for creating a 3D mesh model
    - Develop a 3D modelling tool to generate 3D mesh model based on input parameters
4. Design evaluation and optimization
    - Evaluate the design by generating every commonly used maritime crane with the components in the library
    - Evaluate the design by integrating the mesh model with visualization and simulation environment
5. Design optimization

2 Theoretical basis

We wish that the new design method for modelling for virtual crane's mechanical part could meet two requirements. One is the crane's dimensions could be adjusted easily; the other one is the design process could be focus on the overall operation performance. Those are associated two theories, parametric thinking and kinematics in robotic. Those two theories will be helpful to our design method. They are the use of algorithms and advanced computational techniques not for the sake of drawing shapes, but creating formal possibilities. It is not about producing a solution, but the family of possible outcomes.

2.1 Parametric design for mechanical product

Parametric design is not a new concept and has been always formed a part of design. Parametric thinking introduces the shift in the mind-set between the search for a specific static and defined formal solution, and the design of the specific stages and factors used to achieve it. It is the shift from using CAD software as a representation tool, to do it as a design tool. Parametric Design is the process of designing in environment where design variations are effortless, thus replacing singularity with multiplicity in the design process. Parametric design is done with the aid of Parametric Models. A parametric model is a computer representation of a design constructed with geometrical entities that have attributes (properties) that are fixed and others that can vary. The variable attributes are also called parameters and the fixed attributes are said to be constrained. The designer changes the parameters in the parametric model to search for different alternative solutions to the problem at hand. The parametric model responds to the changes by adapting or reconfiguring to the new values of the parameters without erasing or redrawing.

In parametric design, designers use declared parameters to define a form. This requires rigorous thinking in order to build a sophisticated geometrical structure embedded in a complex model that is flexible enough for doing variations. Therefore, the designer must anticipate which kinds of variations he wants to explore in order to determine the kinds of transformations the parametric model should do. This is a very difficult task due of the unpredictable nature of the design process.

Parametric design has historically evolved from simple models generated from computer scripts that generate design variations [17] every time the script is run with different parametric values, to highly developed structures based on parent child relations and hierarchical dependencies. Currently, parametric CAD software offers sophisticated 3D interactive interfaces that can perform variations in real time, allowing the designer to have more control and immediate feedback when a parameter is changed. Computer implementations of parametric models include structures that show the historical evolution of the model, allowing the designer to go back to a previous stage of the design and apply changes. These changes will be propagated through a chain of dependencies of the modified parameters, which means that a designer can go to any stage, change the value of the parameters, and reconstruct the model. A parametric model will either propagate the changes through the structure and reconfigure the model to the new values, or inform the designer if the modified parameters will create any problems in the solution. More sophisticated parametric modelling software has integrated knowledge-based systems, thus offering better inference to the designer about the consequences of the parametric changes the designer does. Knowledge-based systems in conjunction with parametric modelling are under development and depend on a powerful computational structure based on artificial intelligence, but perhaps are the next big step in the new generation of expert CAD systems.

Regardless of the implementation and sophistication, all parametric models can be categorized into two kinds: those that perform variations and those that generate new designs by combination of parameterized geometrical entities [18]. A parametric model can also be a combination of both kinds, although it is very unusual due to the complexity of the model and the computer performance required.

The benefits of this process are immediate. It is a huge leap in the quality of process, since designers are not bound by their tools anymore; now it will be ones who design their own tools. On the other hand, parametric design is fundamental when minimizing the effort needed to create and test design variants. Generating an automated process eliminates tedious repetitive tasks, the need for complicated calculations on the fly, the possibility of human error, and generates huge shifts in the outcomes with slight variations of the original parameters. It is the difference between using the ‘Cube’ command one thousand times, entering centre point and dimensions, or customizing the design of a ‘Group of Variable Height Cubes’ command out of our own predefined variability rules. Parametric modelling allows re-use of existing products and rapid design modification based on the results of engineering analysis [19]. In a feature –based modelling system [20], the level of detail for feature classes is important. It should be decided among which level of detail they are manipulated. The different levels of detail are form features, functional features and machining features.

For mechanical applications, geometric shapes play an important role in realizing required functions on a machine. The designer has to consider a wide variety of technological criteria, such as kinematic, structural and dynamic properties, assembling constraints, manufacturing costs and so on, for defining the geometries of mechanical parts. Therefore, the mechanical parts are usually designed through iteratively modifying the geometries and evaluating properties from different points of view. In the past, using classic modelling systems, in creating a parametric part of a product, the engineers start from scratch, model features sequentially, one after another, spending time working on the most recent feature without needing to go back to edit previous features. Today, having modern CAD systems, in most cases they don't build models from scratch, but use knowledge data from previous projects, periodically go back to adjust earlier features from time to time. In that process, they'll identify and process most of the dependencies, transforming them in parameters, relations, and constraints etc., saved therefore as knowledge for future projects [21]. The common benefit in parametric modelling is to use advanced construction techniques in modelling and feature recognition in editing phases. It's taken almost 35 years of industry research to get the options where a user is clicking on a face of a model and the system recognize that he is pointing to a feature with parametric values to edit the geometry. The parametric modelling paradigm enables engineers to create new concepts based on previous designs. Users can start with a 2D conceptual model and easily use it as the basis of a 3D model. Parametric modelling tools also enable concept designers to use all types of available data, including ideas, 2D drawings, sketches, surfaces, single parts, or entire assemblies and products. Because these modelling tools offer interoperability in a parametric manner, almost no model re-creation is necessary, giving designers more time to explore a wider range of design alternatives [22].

The designer usually defines the geometries of mechanical parts in terms of geometric relations and the dimensions shown in engineering drawings. Therefore, a geometric modelling system must have the capability of editing geometric relations simultaneously with the defining of geometric models. Using such a system, the designer can define the geometric model in close relation to geometric relations from the beginning of the design process. Koichi Kondo describes the implementation of a geometric modelling system named PIGMOD with a parametric design capability based on non-manifold geometric modelling [23]. The basic idea in his paper is that a set of modelling operations can be so defined that there are correspondences between the geometric constraints and the modelling operations.

In a modern CAD system, a list of curves and surfaces equations, various points coordinates are live updated as the virtual model is conceived, visualized and manipulated on screen by the engineer [24]. The model includes information about surface connectivity (on how the surfaces from a more complex shape are joined, which surfaces are adjacent to each other by which curves, how each surface was obtained etc.) which is very important because all these information is useful in many applications. In the design process, the engineer includes in the model description a list of equations, different attributes and parameters, constraints and relations between the product's parts in assembly. David Weisberg, editor of the Engineering Automation Report, wrote about the parametric modelling [25]: "The problem with a pure parametric design technique that is based upon regenerating the model from its history tree is that, as geometry is added, it is dependent upon geometry created earlier. This methodology has been described as a parent/child relationship, except that it can be many levels deep. If a parent level element is deleted or changed in certain ways, it can have unexpected effects on child-level elements. In some cases the user was forced to totally recreate the model. Some people described parametric designing to be more similar to programming than to conventional engineering design."

2.2 Kinematics in Robotics

One innovation of the design method proposed in this project is focus on the overall operational performance of the crane. Most of the marine cranes can be seen as big robot manipulators and they have similar kinematic performance. So we will combine kinematics expertise from robotics.

The kinematics of a robot manipulator describes the relationship between the motion of the joints of a manipulators consist of a set of rigid links connected together by a set of joints. Manipulator kinematics includes spatial descriptions and transformations, direct kinematics problem and static forces in manipulators.

1. Spatial descriptions and transformations

A 4×4 homogeneous transformation matrix has been introduced to describe the spatial displacement relationship between the two coordinate systems which are the fixed reference coordinate system and the body-attached coordinate system and combine the effects of rotation, translation and scaling. The matrix maps a vector expressed in homogeneous coordinates, from one coordinate system to another coordinate system, consists like the following figure showed.

$$ {}^{A}_{B}\mathbf{T} = \begin{bmatrix} \mathbf{R}_{3\times3} & | & \mathbf{p}_{3\times1} \\ - & | & - \\ \mathbf{f}_{1\times3} & | & 1\times1 \end{bmatrix} = \begin{bmatrix} \text{rotation} & | & \text{position} \\ \text{matrix} & & \text{vector} \\ - & | & - \\ \text{perspective} & | & \text{scaling} \\ \text{transformation} & & \text{factor} \end{bmatrix} = \begin{bmatrix} {}^{A}_{B}\mathbf{R} & | & {}^{A}\mathbf{p}_{Borg} \\ - & | & - \\ \mathbf{f}_{1\times3} & | & 1\times1 \end{bmatrix} $$

Figure 2.1 The homogeneous transformation matrix

2. Direct kinematics problem

For a given manipulator, given the joint angle vector and the geometric link parameters we can get the position and orientation of the end-effector of the manipulator with respect to the reference coordinate system. That is the direct kinematics problem.

Four parameters which are the link parameters (a_i, α_i) determined the structure of the link and the joint parameters (d_i, θ_i) determined the relative connection with neighbouring links are associated with each link of a manipulator. Those four parameters constitute a sufficient set to completely determine the kinematic configuration of each link of a robot arm. Jacques Denavit and Richard Hartenberg introduced this convention in 1955 in order to standardize the coordinate frames for spatial linkages [26] [27]. Those four parameters are known as D-H parameters. And the relations between adjacent links can be represented by 4×4 homogeneous transformation matrix:

$$ {}^{i-1}_{\ \ i}\mathrm{T} = \begin{bmatrix} \mathrm{C}\theta_i & -\mathrm{S}\theta_1 & 0 & a_{i-1} \\ \mathrm{S}\theta_i C\alpha_{i-1} & \mathrm{C}\theta_i C\alpha_{i-1} & -S\alpha_{i-1} & S\alpha_{i-1} d_i \\ \mathrm{S}\theta_i S\alpha_{i-1} & \mathrm{C}\theta_i S\alpha_{i-1} & C\alpha_{i-1} & C\alpha_{i-1} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

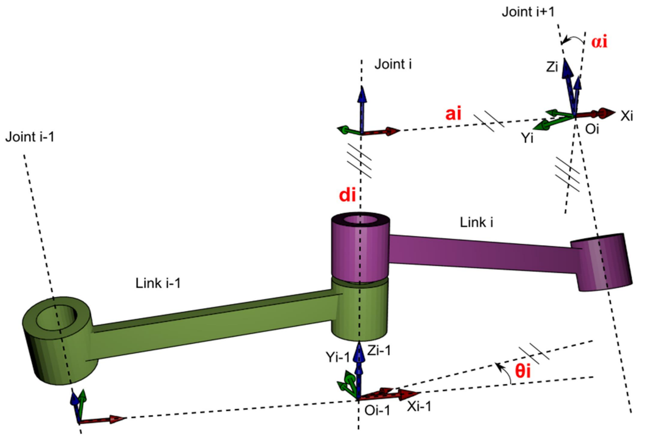


Figure 2.2 The four parameters of classic D-H convention

So the position and orientation of the end-effector of the manipulator can be represented in global coordinate system.

$$ {}^{0}_{\mathrm{n}}\mathrm{T} = {}^{0}_{1}\mathrm{T} * {}^{1}_{2}\mathrm{T} * {}^{2}_{3}\mathrm{T} \cdots {}^{\mathrm{n}-1}_{\mathrm{n}}\mathrm{T} $$

$$ \hat{p}_{xyz} = T * \hat{p}_{uvw} $$

$\hat{p}_{xyz}$ is the position in the global coordinate system.

$\hat{p}_{uvw}$ is the postion in the end-effector-attached coordinate system.

3. Static forces in manipulators

In robotics, we use Jacobians [28] to show the relationships of end-effort velocity and joint velocity, and force and joint torque. Take the position information of the end-effector direct differentiation we can get the Jacobians.

$$ \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{pmatrix} = \begin{pmatrix} f_1(q) \\ f_2(q) \\ \vdots \\ f_m(q) \end{pmatrix} $$

$$ \delta x_1 = \frac{\partial_1}{\partial q_1} \delta q_1 + \cdots + \frac{\partial_1}{\partial q_n} \delta q_n $$

$$ \vdots $$

$$ \delta x_m = \frac{\partial_m}{\partial q_1} \delta q_1 + \cdots + \frac{\partial_m}{\partial q_n} \delta q_n $$

$$ \delta x = \begin{bmatrix} \frac{\partial_1}{\partial q_1} & \cdots & \frac{\partial_1}{\partial q_n} \\ \vdots & \vdots & \vdots \\ \frac{\partial_m}{\partial q_1} & \cdots & \frac{\partial_m}{\partial q_n} \end{bmatrix} \delta q $$

$$ \delta x_{(m \times 1)} = J_{(m \times n)}(q) \delta q_{(n \times 1)} $$

In robotics, the above equation is represented as follows:

$$ \delta x = J \delta \theta \Rightarrow v = J(\theta) \dot{\theta} $$

v is the end-effort velocity.
$\dot{\theta}$ is the joint velocity.

When there is an external force on the end-effector, static forces or torques will be generated. According to virtual work principle, we have,

$$ F \cdot \delta x = \tau \cdot \delta \theta $$

Then

$$ J^T F = \tau $$

F is the static force added in the end-effector.
τ is the torque in each joint.

3 Methods

To achieve the mechanical part design for the VCP, we should at first separate the whole crane into a series of reasonable parts which are created in a parametric way, and then create a library with those parts according to their different features, at last, a desired crane can be assembled with the parts selected from the library.

Based on those steps, we will do as follows:

1. Investigate the crane's type and decompose cranes into components which will be the element in the library.
2. Abstract and simplify those components and use parametric way to make them easy to create.

3.1 Investigation

After checking the rules and regulations in the DNV standard 2-22 lifting appliances, there are no specific requirements about crane's frame. It regulates that only if the stresses on the each section parts can meet the requirements whatever frames of the crane is allowed. VCP is used for crane's concept design or simulation. In VCP we don't do the strength checking for the crane. In this stage we only consider the crane's mechanical moulding and we see crane's each part as rigid body.

Like the figure 3.1 showed, the most common used marine cranes are double-tapered boom crane, telescopic boom crane, knuckle boom crane and telescopic knuckle boom crane.

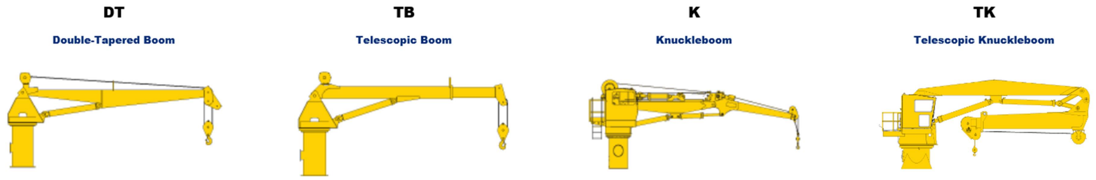


Figure 3.1 Classification of the marine cranes

The double taper boom crane features a fixed length, sealed box section boom for a strong, lightweight, economical crane.

The perfect solution for applications that require reach and compact storage, the telescopic boom crane is available with two to four box boom sections.

Save space and still handle the most challenging jobs with the knuckle boom crane. Flexible enough to manoeuvre into hard to reach locations, the knuckle boom crane is perfect for cargo applications and locations with difficult access from overhead.

The telescopic knuckle boom crane combines the advantages of the knuckle boom and telescopic boom cranes. Extend your reach and get into tight areas with the telescopic knuckle boom design.

And there is also another kind of crane mainly used on the deck of bulk carrier or overload barge for handling a variety of cargo bulks, like the figure 3.2 showed. That crane has a simple kinematic operation, so we will not discuss the lattice boom crane in this project.

Figure 3.2 Lattice boom crane

3.2 Decomposition & create library

From the above section we find that some parts can be common used in different kind type of the cranes. If the crane’s parts can be changed quickly and assembled like LEGO toys, it will be easy to achieve the customization of the crane’s model. To get the correct modelling strategy, with minimal features and steps, spend as little time as possible to obtain a 3D model, firstly we should decompose the crane into several single parts and then use those parts to create a library. From the library, the designer can assemble any crane according their functionalities and requirements.

Feature decomposition is a refinement process which is decomposing parts into specific characteristics, and disassembling the complex design features into simple design features in order to facilitate feature-based mould construction. The disassembled elements should meet the following conditions:

1. The disassembled elements have geometrical and engineering significance.
2. The disassembled elements have reducibility.

The first step of the feature disassemble is feature reduction. Feature reduction is a process which is neglecting secondary features and kept main features in an order. During the process of feature reduction, it will reduce the features which could be described by other features from outside to inside in every step. Feature disassemble is a refinement of the parts step by step, and it is an inverse process of feature reduction.

From the figure 3.1 we can find that all the cranes have a base to support the whole crane; in the outer side of the crane there is an arm with the hook or other actuators; between those two parts there are one or more arms connected to transfer the force, torque and extend the working area. And those base and arms can still be decomposed. For the base, it can be separated into pedestal (make the base turn), kingpost (support the base), supports for the cylinder/winch/drum, cab only for the large crane and joint (connect next arm). For the arm, it can be separated into main body (transfer force, torque and distance), supports for the cylinder/winch/drum and joint.

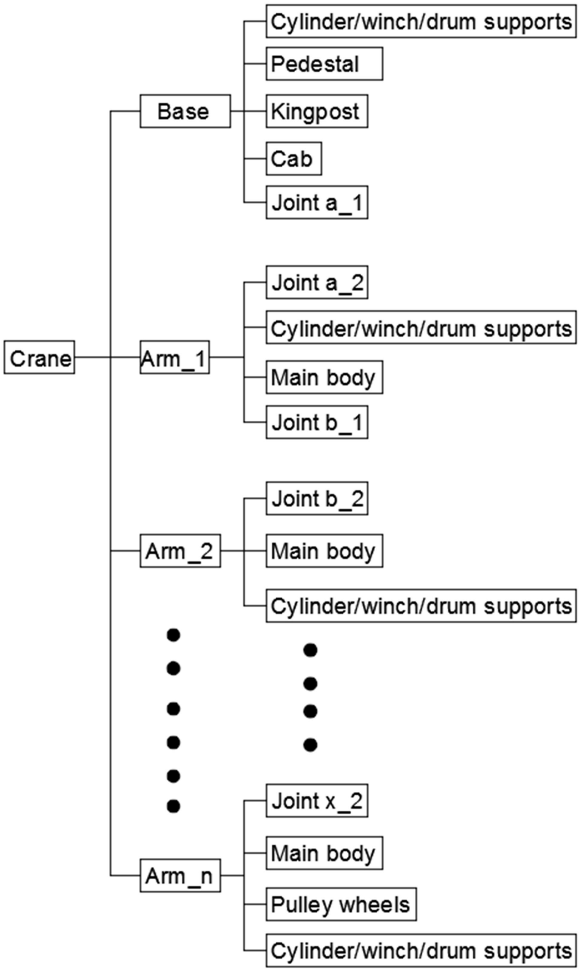


Figure 3.3 Decomposition of the crane

Figure 3.3 shows the decomposition of the crane. From that figure we find some elements have the same functions. If further simplification, in general, the canes can be seen as being constructed by connecting different joints together using rigid links. A number of links are attached serially by a set of actuated joints. So after classified and simplified that decomposition figure, we get a new one like the following figure showed.

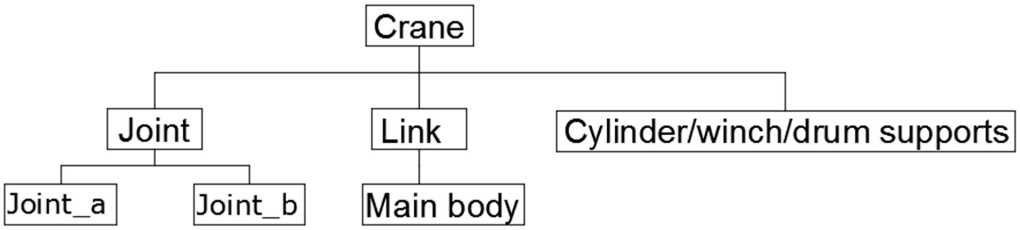


Figure 3.4 Decomposition of the crane

So we finally decompose the crane into 3 components, joint, link and support. From those 3 components we can assemble them into different parts and then use those parts to assemble different cranes.

Therefore the library is created, and by choosing and assembling the components from the library, the designer can easily build a crane with desired configurations like the figure 3.5 showed.

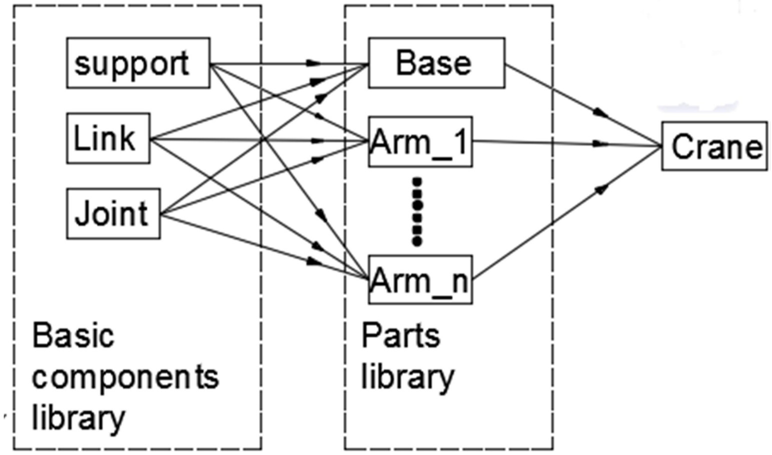


Figure 3.5 Library for the crane's design

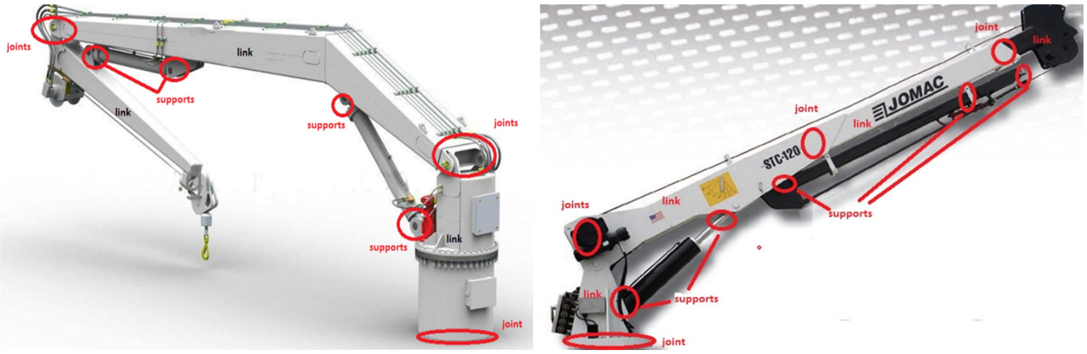


Figure 3.6 Three elements in each crane’s part

The 3 elements can be freely assembled into different parts of the crane like base and arms. We can define the parts as follows:

$\text{Base} = 1 \times jo \qquad 1 \times link + n \times support \quad 1 \times join\ ;$

$\text{Arm\_n} - 1 = 1 \times join \qquad 1 \times link + n \times support + 1 \times join\ ;$

$\text{Arm\_n} = \ 1 \times joint + 1 \times link + n \times support + 0 \times jo \qquad ;$

We will use the parameters to describe those elements. The following part will discuss that how to use a parametric way to create the parts.

3.3 Abstract and simplify

Now we have the library, and how to define the components in the library will be discussed in this section.

The VCP has two innovations:

1. Flexible configuration of marine cranes and verification of operational performance as a part of the design process.
2. Crane should be designed optimised with respect to overall operational performance rather than the performance of individual components and systems.

Innovation 1 requires that the crane’s part dimensions, such as length, width, height and thickness, can be adjusted easily. To achieve Innovation 2, we combine kinematics from robotics and kinematics has relations with each part’s length and angle. So innovations 1 and 2 both have relation with the dimensions of the crane’s part. Those dimensions could be seen as parameters. Then defining those crane’s parts will be used in parametric way. And before that we must abstract and simplify those components so that they will be more suitable for parametric design.

Parametric design defines constraints of the dimensions in the form of rules or algebraic equations, establishes the corresponding reasoning and solution-driven mechanism, implements model transformation, and tries to form a unified database to make changing models' geometric automatically or partial-automatically. When the model needs to be modified or deformed, designers can analyse or modify certain values of the parameters (such as length, angle), then get the corresponding geometric model and keep the mutual constraints in the original model unchanged at the same time. Parametric design automatically maintains relationships between features by geometric constraints and dimensional constraints defined by features, to ensure the consistency and effectiveness of the model changes. It stores as design parameters based on expressions to achieve parameter-driven. That can enable to modify the product geometry dynamically.

To achieve parametric design, first it must be established a parametric model of the part. The so-called parametric model is that the part sketches marked with the parameter name are entered by the user and displayed on the screen. Normally, the structural of the model is unchanged and every parameter's values can be variable. So the part library is necessary for the products contained plenty of modelling.

3.3.1 Kinematics model of the crane

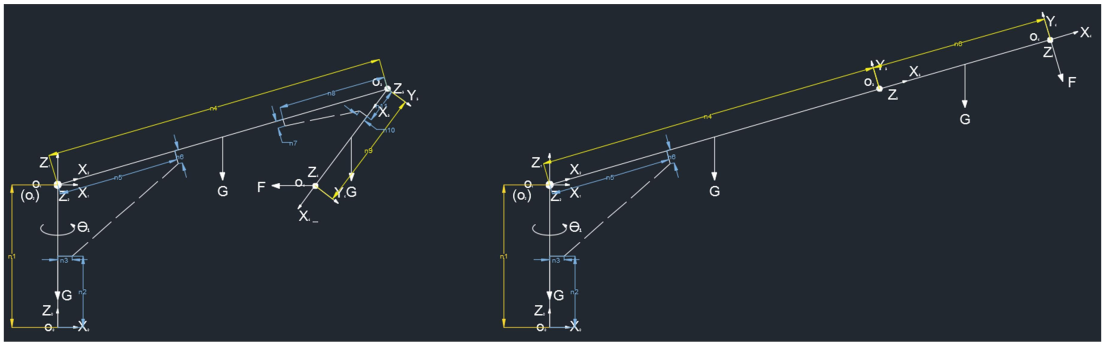


Figure 3.8 Kinematics models of the crane

Kinematics is the study of the mathematics of motion without considering the forces that affect the motion; it deals with the geometric relationships that govern the system and deals with the relationship between control parameters and the behaviour of a system in state space. When doing some kinematics research about the crane, it only needs to be created a kinematics model of the crane and the model needn't to be created as full of description of the shapes. In VCP project, one important purpose of model is used for doing the research of the crane's kinematics appearance. In kinematics model the length for each link is enough to be used and the other dimensions are not important. So the kinematics models, like the figure 3.8 showed, will be the base of the parametric mechanical design in this project.

In those models they contain necessary parameters which are enough to be used in kinematics calculation. In the figure 3.8 it can also be clearly seen that the positions of the cylinder supports are marked and those dimensions will be used to calculate the force needed on each cylinder. The other detail dimensions on each part can be set independently by the designer. In the following part, we will discuss those dimensions in more details. Even without other parameters the length of each part is enough to be used in the kinematics and from section 2.2 we known combined with the working load it also can be calculated the actuated joints' torque. The length of each part also affects the crane's working area. So the length of each part is the main parameter of the crane's model. The main parameters will be firstly defined by the designer.

3.3.2 Parts dimensions analysis

3.3.2.1Base

Base is used to support the whole crane. Its outer shape is not complicated and it can be seen as consisting of a hollow cylinder, supports for next link arm and support for cylinders or winches.

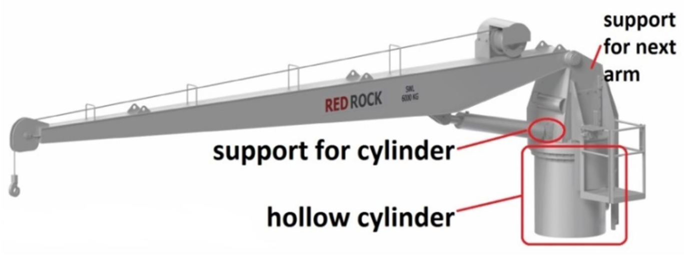


Figure 3.9 The base of the crane

Figure 3.10 Different types of the base

Usually the base shape is changeless and it only has several types like the figure 3.10 showed. Even the new shape appeared, it will be not seemed much different from the existed one. The cylinder support positions on the base can be summarized as 3 types. Now we only use one type to stand for all 3 types like the figure 3.11 showed. Because the dimensions on that type base could represent all 3 types.

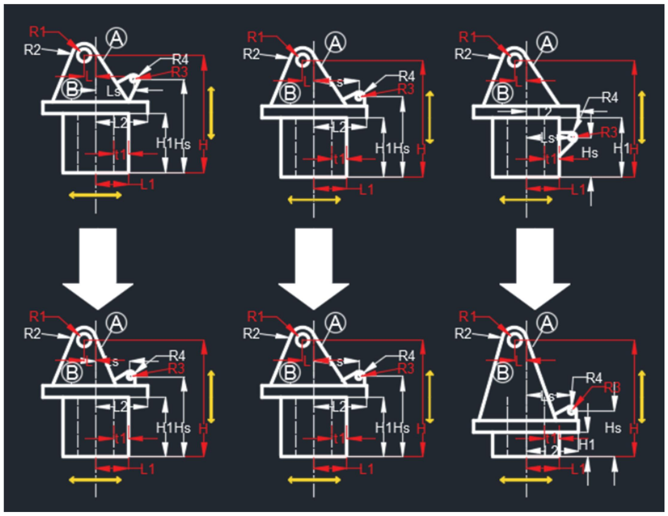


Figure 3.11 3 types of base

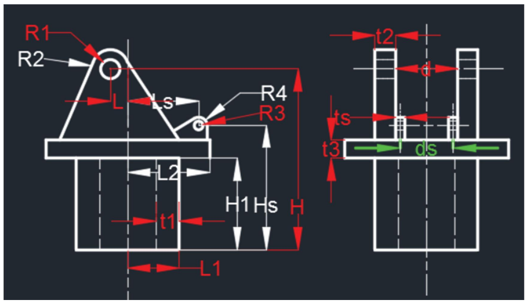


Figure 3.12 The sketch of the base

In the figure 3.12 there are a lot of dimensions marked on the sketch. Some dimensions are independent parameters and the others are coupling parameters. The detailed description is in the following table. How to classify those dimensions should also consider the factor about mechanical moulding beside the kinematics needs. Because we wish when the designer changed the main dimensions of the part, some of the other dimensions can be roughly adjusted automatically so that the part can still be maintained a certain structure. The rule will be also used in other parts.

Independent parameters	default values
L_1, H, L, d, R_1, R_3, t_1, t_2, t_3, ts, ds	Decide by designer
Coupling parameters	values
H_1	$H_1=x_1 \cdot H$, (x_1 is a proportion changed from 0 to 1);
L_2	$L_2=L_1+y_1$,(y_1 is a positive number);
L_s	$L_s=L_2-y_2$,(y_2 is a positive number);
H_s	$H_s=H-H_1-t_3+y_3$,(y_3 is a positive number);
R_2	$R_2=R_1+y_4$,(y_4 is a positive number);
R_4	$R_4=R_3+y_5$,(y_5 is a positive number);

Table 3.1 Parameters in the base

In the independent parameters, $\mathbf{R_1}$, $\mathbf{R_3}$, $\mathbf{t_1}$, $\mathbf{t_2}$, $\mathbf{t_3}$, $\mathbf{t_s}$ can be just set once and are not needed to be adjusted when other independent parameters are changed because we don't need to do the structure analysis.

The space between the cylinder supports has two following forms like the figure 3.13 showed. In the real crane when hydraulic cylinder is used, the cylinder support's type may be one or two according to the cylinder's connection part's type.

Figure 3.13 The connection part of the cylinder

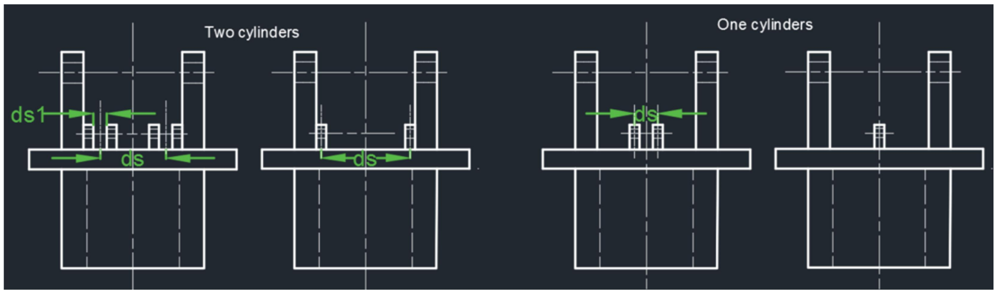


Figure 3.14 Two solutions

For those two kinds of connection types, we have two solutions like the figure 3.14 showed. Those two solutions will be also used in the supports on other parts.

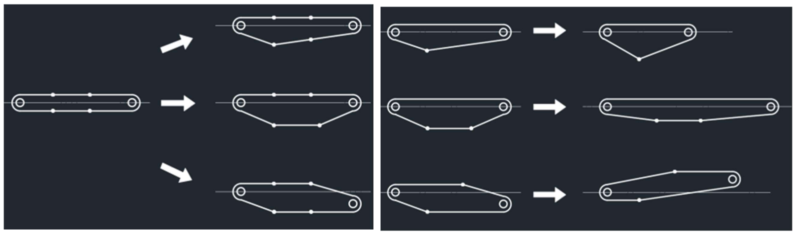
When the base is used two cylinders to support the next arm, they are liked the left part of the figure 3.14 showed. When the base is only used one cylinder to support the next link arm, they are liked the right part of the 3.14 showed.

3.3.2.2Arm_n-1

From the figure 3.8 we can find that the number of the crane's arm is changed from 1 to n (n>1) except the base. So we define the arm between the base and last arm as arm_n-1. They all have the same functions which are transferring force, torque and extending the working area of the crane.

The arm_n-1 has a variety of shapes according to the different uses. We will discuss them separately.

According to different shapes, we have two schemes to create the model liking the following figure showed. The first one is we only create one model and then though changing some critical dimensions to get new models. The second one is for each specific shape we create a model and then though changing key dimensions to get new models.



Scheme 1 Scheme 2

Figure 3.15 2 schemes to create the arm model

	Scheme 1	Scheme 2
Initial work	Less (+)	More (-)
Key parameters	More (-)	Less (+)
Relations between parameters	More (-)	Less (+)
Operations to get a new model	Complicated (-)	Simple (+)
Time cost for creating a new model	More (-)	Less (+)
Comprehensive evaluation	(---)	(+++)

Table 3.2 Evaluation of two schemes

Compared to those two schemes, from the upper chart we can see scheme 2 is a better choice.

We can divide the arm_n-1's shape into 2 types. One is both the boom's two joints are rotating type like the knuckle boom crane's arm. The other one is the arm's two joints are rotating type and prismatic type like the telescopic boom crane.

Now we first discuss the two rotating joint type arm like the figure 3.16 showed.

Figure 3.16 Knuckle boom crane

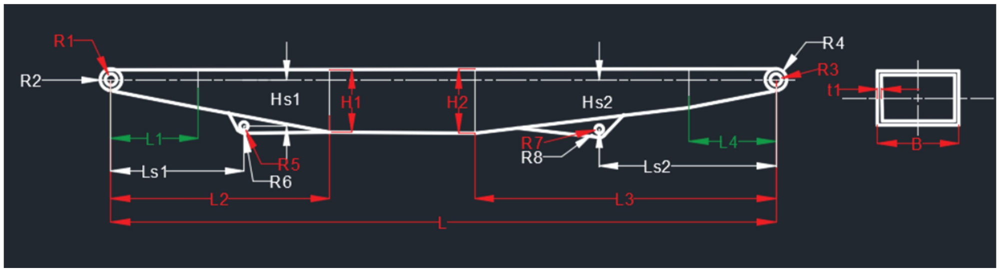


Figure 3.17 The sketch of knuckle type arm_n-1

The detailed description for the dimensions is in the following table.

Independent parameters	Default values
R_1, R_5, L, H_1, H_2, R_7, R_3, t_1, B	Decide by designer
Coupling parameters	Values
R_2	$R2=R_1+y_1$,(y_1 is a positive number);
R_4	$R4=R_3+y_2$,(y_2 is a positive number);
L_2	$L_2= x_1 \cdot L$, (x_1 is a proportion changed from 0 to 1);
L_3	$L_3= x_2 \cdot L$, (x_2 is a proportion changed from 0 to 1);
Ls_1	$Ls_1=L_2-y_3$,(y_3 is a positive number);
Ls_2	$Ls_2=L_3-y_4$,(y_4 is a positive number);
Hs_1	$Hs_1= Ls_1 * \frac{H_1}{L_2}$;
Hs_2	$Hs_2= Ls_2 * \frac{H_2}{L_3}$;

Table 3.3 Parameters in knuckle type arm

In the independent parameters, $\mathbf{R_1}$, $\mathbf{R_5}$, $\mathbf{t_1}$, $\mathbf{R_7}$, $\mathbf{R_3}$ can be set as a default value and are not needed to be adjusted when other independent parameters are changed.

The way dealing with the distance between the supports on the cross section of the boom is the same with the one used in the base. But the support's position on this part of the crane usually has two locations. One is located on the side of the arm like the figure 3.18 A showed; the other one is located at the bottom of the arm like the figure 3.18 B showed. As to those situations, we can create two models for the same shape's part, one is used for situation A and the other is used for situation B. For the situation A the location of the cylinder support is only considering in vertical and horizontal direction because in the cross section direction they are attached on the outer side of the part. For the situation B we have discussed before.

A B

Figure 3.18 Support positions

The dimension $\mathbf{L_1}$, $\mathbf{L_4}$ will be defined later.

Now we discuss the other type arm like the figure 3.19 showed.

Figure 3.19 Telescopic boom

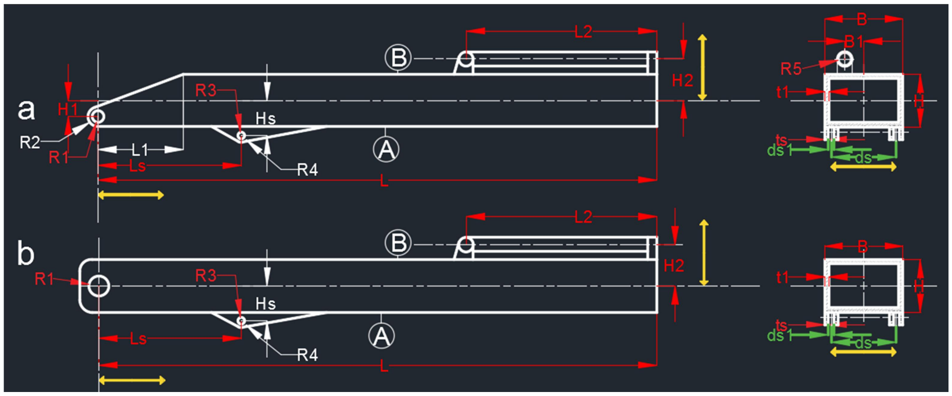


Figure 3.20 The sketch of telescopic type arm_n-1

The detailed description is in the following table.

Independent parameters	Default values
R_1, R_3, L, H, R_5, t_1, B, B_1	Decide by designer
Coupling parameters	Values
R_2	$R2=R_1+y_1$,(y_1 is a positive number);
H_1	$H_1=H/2-R_2$;
H_2	$H_2=H/2+y_4$,(y_4 is a real number);
R_4	$R4=R_3+y_2$,(y_2 is a positive number);
L_2	$L_2=x_1 \cdot L$, (x_1 is a proportion changed from 0 to 1);
Ls	$Ls=x_2 \cdot L$, (x_2 is a proportion changed from 0 to 1);
Hs	$Hs= H/2+y_3$,(y_3 is a real number);

Table 3.4 Parameters in telescopic type arm

Figure 3.21 The two types of connection between the base and arm

In the figure 3.21 there are two types of connection between the base and arm. We call the left one Cross connection and call the right one Surrounding connection.

For the cross connection:

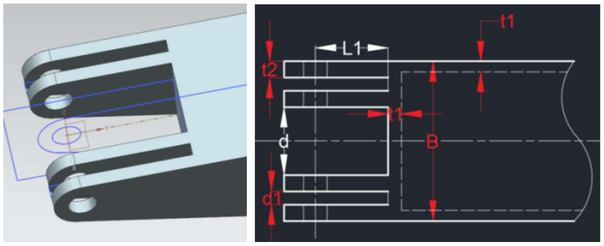


Figure 3.22 The sketch of the cross connection

$$\begin{cases} 2 \times d_1 + 4 \times t_s + d = B \rightarrow d = B - 2 \times d_1 - 4 \times t_s \\ L_1 = x \cdot L_2, x \text{ is a proportion changed from 0 to 1} \end{cases}$$

t_2, d_1 are independent parameters, and d is coupling parameters.

For the surrounding connection:

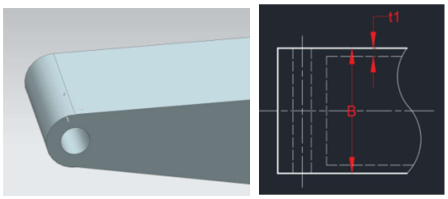


Figure 3.23 the sketch of the surrounding connection

In this type of connection, it doesn't need **L_1**.

The upper processing method also applies to the **L_4**.

3.3.2.3Arm_n

We define the last arm of the crane as arm_n. The difference between arm_n and arm_n-1 is that the terminal actuator will be fixed and its function still includes transferring force, torque and extending the working area of the crane.

The arm_n also has a variety of shapes according to the different uses. We take 3 type of arm for example, like figure 3.24, 3.25 and 3.26 showed.

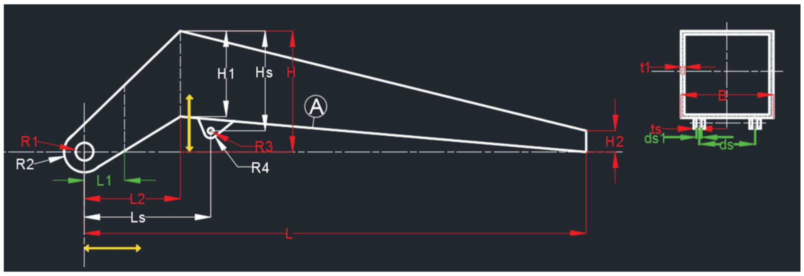


Figure 3.24 The sketch of one kind of arm

The detailed description is in the following table.

Independent parameters	Default values
R_1, L, H, R_3,H_2, t_1, B	Decide by designer
Coupling parameters	Values
R_2	$R_2=R_1+y_1$,(y_1 is a positive number);
L_2	$L_2=x_1 \cdot L$, x_1 is a proportion changed from 0 to 1);
Ls	$Ls=L_2+y_2$,(y_2 is a positive number);
H_1	$H_1=y_3 \cdot H$,(y_3 is a proportion changed from 0 to 1);
Hs	$Hs= (L-L_s)* \frac{H-H_1}{L-L_2}$;
R_4	$R_4=R_3+y_4$,(y_4 is a positive number);

Table 3.5 Parameters in one kind of arm

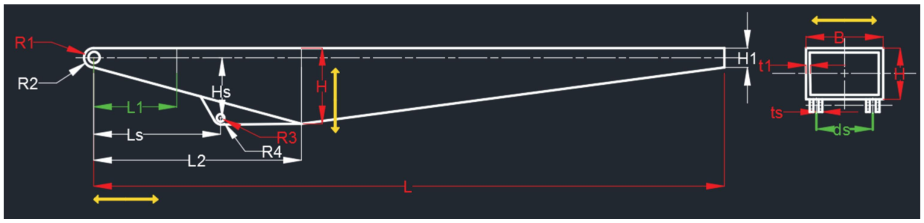
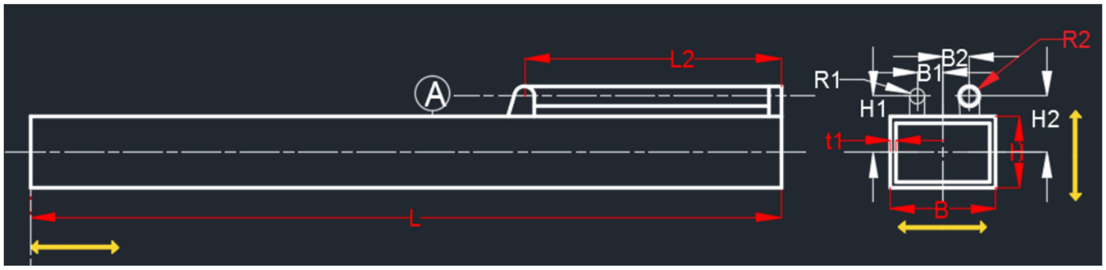


Figure 3.25 The sketch of another kind of arm

The detailed description is in the following table.

Independent parameters	Default values
R_1, L, H, R_3,H_2, t_1, B	Decide by designer
Coupling parameters	Values
R_2	R_2=R_1+y_1,(y_1 is a positive number);
Ls	Ls=L_2+y_2,(y_2 is a positive number);
L_2	L_2=x_1·L, x_1 is a proportion changed from 0 to 1);
H_1	H_1=y_1·H,(y_1 is a proportion changed from 0 to 1);
Hs	Hs= $(L-L_s)*\frac{H-H_1}{L-L_2}$;
R_4	R_4=R_3+y_4,(y_4 is a positive number);

Table 3.6 Parameters in another kind of arm



Figuer 3.26 The sketch of the third kind of arm

The detailed description is in the following table.

Independent parameters	Default values
R_1, R_2, L, H, R_5, t_1, B, B_1, B_2	Decide by designer
Coupling parameters	Values
R_2	R_2=R_1+y_1,(y_1 is a positive number);
H_1	H_1=H/2-R_2;
H_2	H_2=H/2+y_4,(y_4 is a real number);
R_4	R_4=R_3+y_2,(y_2 is a positive number);
L_2	L_2=x_1·L, (x_1 is a proportion changed from 0 to 1);

Table 3.7 Parameters in the third kind of arm

In the independent parameters, $\mathbf{R_1}$, $\mathbf{R_3}$, $\mathbf{t_1}$ can still be set as default values and are not needed to be adjusted when other independent parameters are changed.

The way dealing with the distance between the supports on the cross section of the arm is the same with the way used in the base. The solution of the connection joint is the same with one used in the Arm_n-1.

3.3.3 Design datum

To get the parameters in the model easily and locate easily during the assembling process, we determine the design datum for each part.

Datum is the origin for both tolerances and measurements. As the datum to be the start point, to determine the location of the plane, line or point on the part or component, datum could be plane (plane of symmetry, end plane and so on), line (centre line) or point.

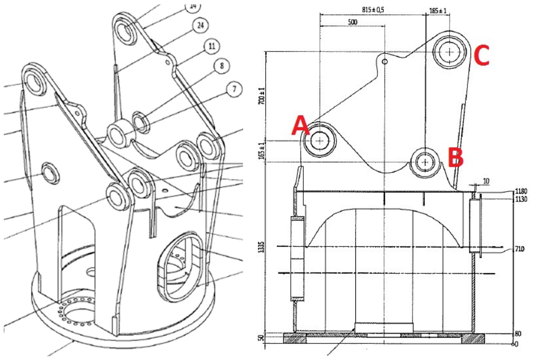
According to the different applications and functions, datum can be divided into two categories: design datum and process datum. In this project, we only discuss design datum. Design datum is a datum used for determining the location of other point, line or plane on the part drawing according to the structure of the part and designing requirements. With the design datum, designers can calibrate and calculate some point, line, surface's size or the relationship of the locations. It may be a real point, line, plane; it also can be imaginary, such as centre line, the centre point or symmetry plane.

Between the drawing used for real crane's design and the drawing used for VCP modelling, the design datum selection has some differences. The following part will discuss them to make the dimension transferring between those two drawing feasible.

1. The design datum of the real crane product

   The design drawings of engineering component are followed following rules:

a. A good datum feature is a 'functional' feature that most influences the location or orientation of a component. A functional feature is often a mating feature used in assembling operations.
b. A good datum feature should be easily accessible for assembly and manufacturing.
c. A good datum feature should be easily accessible for inspection and gauging.



A B

Figure 3.27 The sketch of base

We take a real crane base's sketch of side view for example like the figure 3.27 showed. In the vertical direction, hole A is the design datum of the hole B and C; hole B is the design datum of the bottom plane. In the horizontal direction, the vertical center line is the design datum of the hole A; hole A is the design datum of the hole B; hole B is the design datum of the hole C. The distances from hole A to C and from hole A to B in vertical and the distances from hole A to B and from hole B to C in horizontal are main dimensions. In the real product, those holes' positions are important in the assembling between base and next arm and in parts procesing .

2. The design datum in the part model in the library

The model in the figure 3.8 could be seen a simplified crane mode. It contains most of the necessary parameters used for kinematics calculation, also shows the assembly relations between each part and modeling sequence; O_0, O_2, O_3 and each part's center line are the design datums; the dimensions marked yellow color are main dimensions which ensure the correct locations.

Now we will discuss the datums and dimensions marking of each part in details.

Base

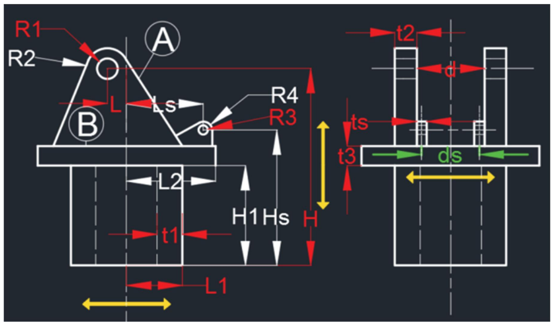


Figure 3.28 The sketch of the base

Figure 3.28 is the sketch of the base. The vertical central line and the bottom plane are the design datums for other dimensions in vertical and horizontal directions. The most of the important dimensions can be adjusted from those two datums.

L_1, **L_2**, **L**, **H_1**, **H**, **R_2** decide the outline of the base; **Ls**, **Hs**, **ds** decide the support position of the hydraulic cylinder; **R_1**, **R_3**, **t_1**, **t_2**, **t_3**, **d** decide the mass of the base (we assume we have known the density of the crane).

When the designer wants to get a new base, the first setting parameters are **L_1** and **H**. Then **H_1**, **L_2** can be adjusted automatically to make the base shape keeping a certain reasonable scale.

Actually the cylinder support is always welded in the plane A or B. So the design datum of the support's location should be plane B. But if the support's location are marked like figure 3.28 showed, it will directly get the distances n_2 and n_3 showed in figure 3.8 and that will be easy to ues for the calculation's need. To balance those, we still use the bottom and vertical Centre line as design datums and when setting the values of the **Hs** ($Hs=H-H_1-t_3+y_3$, y_3 is a positive number) and **Ls** ($Ls=L_2-y_2$, y_2 is a positive number), the datum of dimension y_3, y_2 are plane B. If the designer wants to adjust the position of the support, he only needs to change the y_3 and y_2's values.

Arm_n-1

We have divide the arm_n-1's shape into 2 types. As for two rotating type arm, the connection line between the two joints' centres is the design datum for the vertical direction. As for one rotating and one prismatic type arm, the central line of the arm's prismatic part is the design datum for the vertical direction.

No matter how the arm's shape changes, its cross section is always symmetrical geometry. So the design datum for the cross section direction is the symmetry plane of the boom.

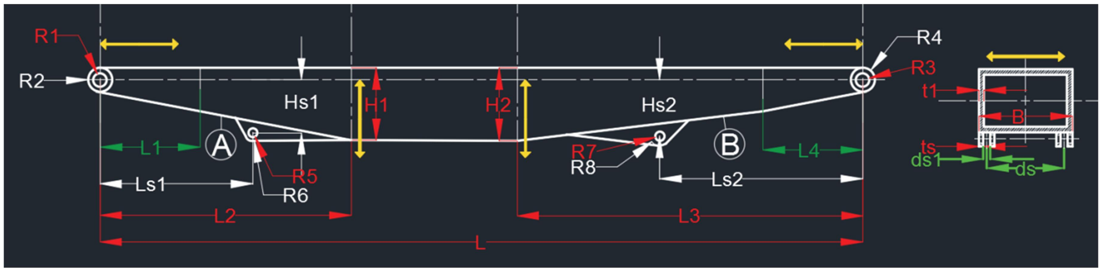


Figure 3.29 The sketch of the arm with two rotating joints

Figure 3.29 is the sketch of the arm with two rotating joints. The central points of the two joints are the design datums for the horizontal direction, and the central ponit of the left joint is the design datum for the location of the right joint; the connection line between two joints is the design datum for the vertical direction; the symmetry plane of the boom is the design datum for the cross section direction. Most of the important dimensions can be marked from those three datums.

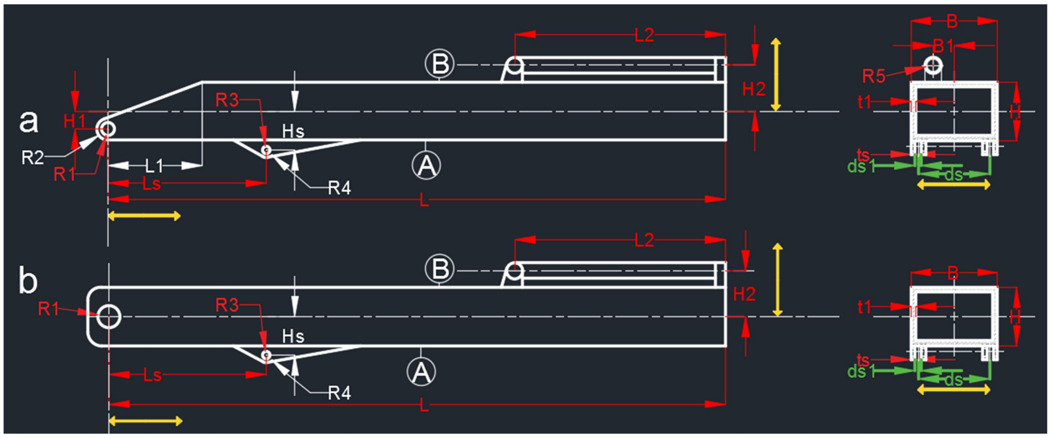


Figure 3.30 The sketch of arm with a rotating joint and a prismatic joint

Figure 3.30 is the sketch of the another kind of arm. There are two types of the arm in the figure 3.30, and they have the same determination of the datums. The central line of the joint is the design datum for the horizontal direction; the central line of the boom's main body is the design datum for the vertical direction; the symmetry plane of the boom is the design datum for the cross section direction. Most of the important dimensions can be marked from those three datums.

For both kinds of arms, $\mathbf{R_2}$, $\mathbf{R_6}$, $\mathbf{L_2}$, $\mathbf{H_1}$, $\mathbf{H_2}$, **L**, $\mathbf{L_3}$, $\mathbf{R_8}$, $\mathbf{R_4}$, **B** decide the shape of the arm; $\mathbf{Hs_1}$, $\mathbf{Ls_1}$, $\mathbf{Hs_2}$, $\mathbf{Ls_2}$, **ds** decide the support position of the hydraulic cylinder; $\mathbf{R_1}$, $\mathbf{R_3}$, $\mathbf{R_5}$, $\mathbf{R_7}$, $\mathbf{t_1}$, **ts** decide the mass of the arm.

When the designer wants to get a new arm, the first setting parameters are **L**, $\mathbf{H_1}$, $\mathbf{H_2}$ and **B**. Then we wish $\mathbf{L_2}$, $\mathbf{L_3}$ can be adjusted automatically keep the arm's shape maintain a certain reasonable scale.

Similarly on the arm the design datum of the support's location should be plane A and B. We also want to get the value of n_5, n_6, n_7, n_8 in the figure 3.8 directly to make the data output easily. To meet those two requirements, we still use the datums marked in the figure 3.30 and we set the values of the $\mathbf{Ls_1}$ ($Ls_1=L_2-y_3$, y_3 is a positive number), $\mathbf{Hs_1}$ ($Hs_1= H_1+y_5$, y_5 is a real number), $\mathbf{Ls_2}$ ($Ls_2=L_3-y_4$, y_4 is a positive number), $\mathbf{Hs_2}$ ($Hs_2= H_2+y_6$, y_6 is a real number). If the designer wants to adjust the position of the support, he only needs to change the y_3, y_5, y_4 and y_6's value.

Arm_n

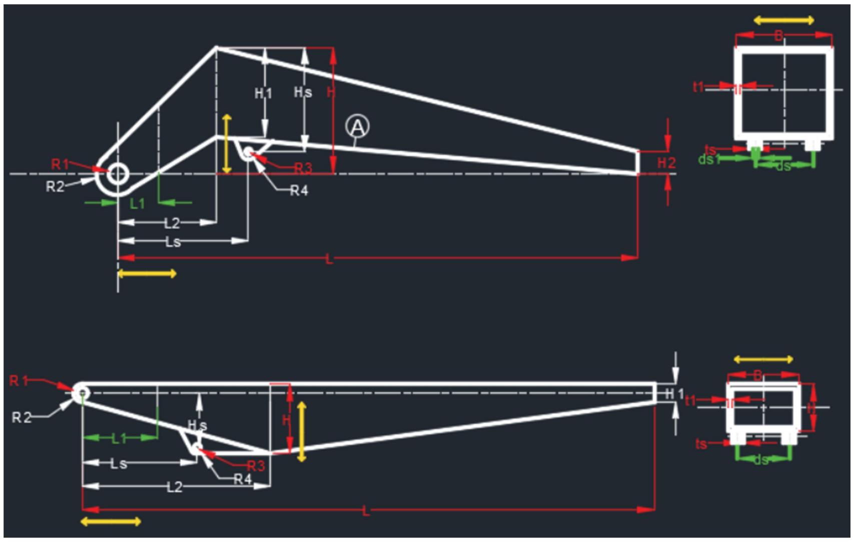


Figure 3.31 The sketches of two types arms

The upper figure is the sketches of the two types arms. They have the same design datums. The central line of the joint is the design datum for the horizontal direction; the connection line between the joint and the end tip of the arm is the design datum for the vertical direction; the symmetry plane of the arm is the design datum for the cross section direction. Most of the important dimensions can be adjusted from those three datums.

R_2, **L_2**, **H**, **H_1**, **L**, **H_2**, **R_4**, **B** decide the shape of the arm; **Hs**, **Ls**, **ds** decide the support position of the hydraulic cylinder; **R_1**, **t_1**, **ts** decide the mass of the arm.

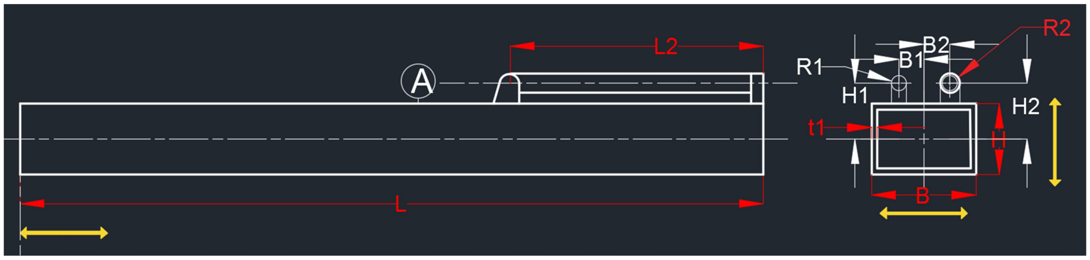


Figure 3.32 The sketch of another type arm

Figure 3.32 is the sketch of another type arm used in the telecopic boom crane. The head face of the arm in the left side is the design datum for the horizontal direction; the central line of the arm's main body is the design datum for the vertical direction; the symmetry plane of the arm is the design datum for the cross section direction. Most of the important dimensions can be adjusted from those three datums.

H, **L** and **B** decide the shape of the arm; **B_1**, **B_2**, **H_1** and **H_2** decide the support position of the hydraulic cylinder jacket; **t_1** decide the mass of the arm.

When the designer wants to get a new arm, the first setting parameters are **L**, **H** and **B**. Then we wish $\mathbf{L_2}$, $\mathbf{H_1}$ and $\mathbf{H_2}$ can be adjusted automatically to make the shape of the arm keeping a certain reasonable scale.

Similarly on the arm the design datum of the support's location should be plane A. We also want to get the value of n_{10}, n_{11}in the figure 3.8 directly to make the data output easily. To meet those two requirements, we still use the datums marked in the figure 3.32 and we set the values of the **Ls** ($Ls=L_2+y_2$, y_2 is a positive number), **Hs** ($Hs= H_1+y_3$, y_3 is a real number). If the designer wants to adjust the position of the support, he only needs to change the y_2 and y_3's value.

3.3.4 Parameter optimization

In the section 3.3.2.1, 3.3.2.2, 3.3.2.3, we have divided the parts' dimensions into independent parameters and coupling parameters. That classification only show the difference of the parameters defined in each parts and it doesn't indicate the importance and hierarchical relationship among the parameters. Now we will follow the following rules to optimize those parameters to make the relations among the parameters more obviously.

According to the different importance of the dimensions on the part drawings, the dimensions can be divided into two categories:

a. Main dimension

   The dimensions which can ensure the correct locations of the parts in the machine and accuracy of the assembly are all belonged to the main dimensions, and such dimensions will directly affect the performance of the machine. In product design, the main dimensions generally have the relation with assemble dimension chain, and should be machining with high precision.

b. Free dimension

   In the part drawing, some dimensions don't affect the performance of the machine, and also do not affect the mating, assembling between the parts, and we call them free dimension. In product design, free dimension has nothing to do with assembly Dimension Chain. It has a low dimensional accuracy.

In the following chats, main parameters belong to main dimensions; secondary parameters belong to free dimension.

Base:

	Main parameter	Secondary parameters	
		Independent parameters (set a default value by designer)	Coupling parameters
Vertical direction	H	t_3	$H_s=x_1 \cdot H$, (x_1 is a proportion changed from 0 to 1); $H_1=H_s-t_3-y_3$,(y_3 is a positive number);
Horizontal direction		L_1, L, t_1, t_2, d, ds, ts	$L_2=L_1+y_1$,(y_1 is a positive number); $Ls=L_2-y_2$,(y_2 is a positive number);
Other direction		R_1, R_3	$R2=R_1+y_4$,(y_4 is a positive number); $R4=R_3+y_5$,(y_5 is a positive number);

Table 3.8 Parameters in the base

The dimensions have been marked in the figure 3.28.

Arm_n-1:

	Main parameter	Secondary parameters	
		Independent parameters (set a default value by designer)	Coupling parameters
Vertical direction		H_1,H_2	$Hs_1= Ls_1 * \frac{H_1}{L_2}$; $Hs_2= Ls_2 * \frac{H_2}{L_3}$;
Horizontal direction	L	B, ds, ds_1, ts	$L_2= x_1 \cdot L$, (x_1 is a proportion changed from 0 to 1); $L_3= x_2 \cdot L$, (x_2 is a proportion changed from 0 to 1); $Ls_1=L_2-y_3$,(y_3 is a positive number); $Ls_2=L_3-y_4$,(y_4 is a positive number);
Other direction		R_1, R_5, R_7, R_3, t_1	$R2=R_1+y_1$,(y_1 is a positive number); $R4=R_3+y_2$,(y_2 is a positive number);

Table 3.9 Parameters in knuckle type arm

The dimensions have been marked in the figure 3.29.

	Main parameter	Secondary parameters	
		Independent parameters (set a default value by designer)	Coupling parameters
Vertical direction		H	$H_1 = y_1$,($y_1 \in [0, H/2]$); $H_2 = H/2 + y_2$,(y_2 is a positive number); $\begin{cases} bottom: H_s = H/2 + y_{3,} \text{ (}y_3\text{ is a positive number} \\ side\ plane: H_s = y_3, (y_3 \in [-H/2, H/2]); \end{cases}$
Horizontal direction	L	B, ds, ds_1, ts, L_1	$L_s = x_1$,($x_1 \in [0, \mathrm{L}/2]$); $L_2 = x_2$,($x_2 \in [0, \mathrm{L} - L_1]$);
Other direction		R_1, R_3, t_1	R2=$R_1 + y_4$,(y_4 is a positive number);

Table 3.10 Parameters in telescopic type arm

The dimensions have been marked in the figure 3.30.

Arm_n:

	Main parameter	Secondary parameters	
		Independent parameters (set a default value by designer)	Coupling parameters
Vertical direction		H	$H_1 = y_1 \cdot H$,($y_1 \in [0,1]$); $H_2 = y_2$,($y_2 \in [0, H_1]$); Hs= $(L-L_s) * \frac{H-H_1}{L-L_2}$;
Horizontal direction	L	B	$L_2 = x_1$,($x_1 \in [0, \mathrm{L}/2]$); Ls=$L_2 + x_2$,($x_2$ is a positive number);
Other direction		R_1, R_3, t_1	$R_2 = R_1 + y_3$,(y_3 is a positive number); $R_4 = R_3 + y_4$,(y_4 is a positive number);

Table 3.11 Parameters in one kind of arm

The dimensions have been marked in the figure 3.31.

	Main parameter	Secondary parameters	
		Independent parameters (set a default value by designer)	Coupling parameters
Vertical direction		H	$H_1=y_1$,($y_1 \in [0, H_1]$); Hs= $L_s * \frac{H}{L_2}$;
Horizontal direction	L	B	$L_2=x_1$,($x_1 \in [0, L/2]$); Ls=L_2-x_2,(x_2 is a positive number);
Other direction		R_1, R_3, t_1	$R_2=R_1+y_2$,(y_2 is a positive number); $R_4=R_3+y_3$,(y_3 is a positive number);

Table 3.12 Parameters in another kind of arm

The dimensions have been marked in the figure 3.31.

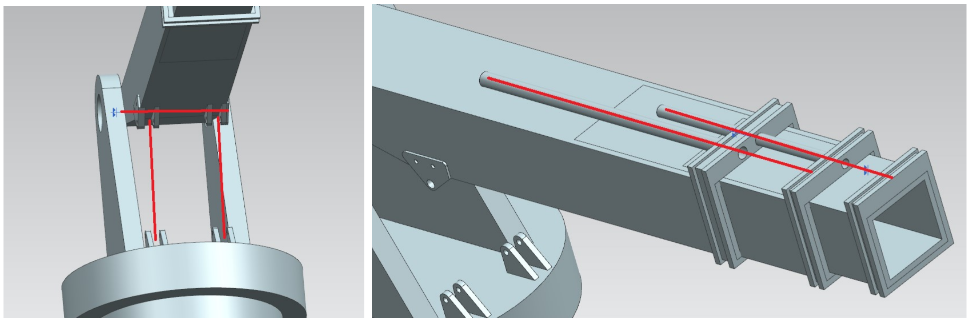
	Main parameter	Secondary parameters	
		Independent parameters (set a default value by designer)	Coupling parameters
Vertical direction		H	H_1= H/2+y_1,($y_1$is a positive number); H_2= H/2+y_2,(y_2 is a positive number);
Horizontal direction	L	B, L_2	
Other direction		R_1, R_2, t_1, B_1, B_2	

Table 3.13 Parameters the third kind of arm

The dimensions have been marked in the figure 3.32.

3.3.5 Assembling

When the base, arm_n-1, arm_n are assembled, we should avoid collision between each part and ensure the symmetry plane of the cylinder supports located at different part in the same axis. So **d** in base and **B** in the arm_n-1 should be matched and **ds** in each part should be same like the red lines marked in the figure 3.33 A showed. When the telecopic type arms are assembled, the cylinder jacket's central lines should be always kept in a line like the red line marked in the figure 3.33 B showed.



A B

Figure 3.33 Two situations during the assembly

We have established the library, so that the crane showed in the figure 3.1 could be assembled with the parts in the library. And when assembled, it should also be followed the assembling rules discussed before.

3.3.6 Summary

According to the discussion above, the parametric design method of the marine crane's mechanical part is as follows:

1. **Parameter abstraction**.
    1) **Main parameters abstraction**. For the marine crane, the length of each part is the main parameter. It affects the working area of the crane and this is an important factor in concept design. If the working area has been given, we can decide each part's length. Then with the crane's type, **the kinematics model** of the crane can be drew. Once the kinematics model decided, the driving moment for each joint can be calculated and that will be used for choosing or designing the actuators.
    2) **Parts parameters abstraction**. The purpose of parts parameters abstraction is to classify the parameters contained in the parts and to extract the parameters which can directly drive other parameters. The classification of parameters should be followed the following principles:
        a) The main parameter has been defined above and it is the length of each part.
        b) Other parameters in the part are secondary parameters. In the secondary parameters the parameters which are associated with other parameters and decide the part's general frame are coupling parameters; parameters which could be set as

default values and do not affect other dimensions in the parts and decide the frame's details are independent parameters.

2. **Component library creating and coordinate system setting**.

1) **Elements decomposition**. The crane is assembled by some parts and those parts have some similar structures like the figure 3.2.3 showed. Those structures are the base modules of assembling the crane. So the crane can be decomposed by several modules according to the different features or functions which are defined by the designer. For example for the hydraulic dive crane, the basic modules could be support, link and joint; for the motor drive crane, the basic modules could only contain joint and link.

We decomposed the crane into 3 modules, support, link, joint and those are best for our target.

Support can be the support for hydraulic cylinder or the support for winch. Its function is used for connecting the hydraulic cylinder or fixed the winch.

Link is the main structure of each part. It purely delivers the force and torque.

Joint is the connections between two parts. It has two types: revolution and prismatic.

The 3 elements can be freely assembled into different parts of the crane like base and arms.

$\mathrm{Base} =$

$1 \times \mathrm{joint(rolling\ type)} + 1 \times \mathrm{link} + \mathrm{n} \times \mathrm{support} + 1 \times \mathrm{joint(rotation\ type)};$

$\mathrm{Arm}_{\mathrm{n\_1}} = 1 \times \mathrm{joint(rotation/prismatic\ type)} + 1 \times \mathrm{link} + \mathrm{n} \times \mathrm{support} + 1 \times \mathrm{joint(rotation/prismatic\ type)};$

$\mathrm{Arm}_{\mathrm{n}} = 1 \times \mathrm{joint(rotation/prismatic\ type)} + 1 \times \mathrm{link} + \mathrm{n} \times \mathrm{support} + 0 \times \mathrm{joint};$

2) **Coordinate system setting.** The purpose of this step is to unify the coordinate system for each part and also regulate the datum or benchmark in each part.

All the dimensions marked on the crane's parts should be met the following rules:

We define x direction is from one joint central to the other joint central; the plane where the central points of two joints and the central point of the support are all on is the x-y plane; y direction perpendicular to the x direction; z direction perpendicular to the x-y plane.

In the x direction, the benchmark and datum should be the central of the first joint. Sometimes the central of the second joint can also be the original point for some dimensions. For example the original of the support position of the hydraulic cylinder which is driving the next arm is the second joint central because that defining is more intuitive to the designer. The distance between the two joints will be the base and every dimension in x direction will have relation with it.

In the y direction, for the axisymmetric link the benchmark and datum should be link's symmetry axis and for the plane symmetric link the benchmark and datum should be the connection line between two joints' central. The height of the biggest cross section will the base and every dimension in vertical will have relation with it.

In the z direction, the benchmark and datum should be the link's symmetry plane. The width the parts main body will be the base and every dimension in the z direction will have relation with it.

3. **Getting the geometric model**. With the parameters defined above, we can create 3D models in CAD software or programming language.

   The realization of the assembly could be in varied forms. It could have the separate models first and then be assembled; it also can be in one model using dimensions to mark the 3 elements like the figure 3.34 showed.

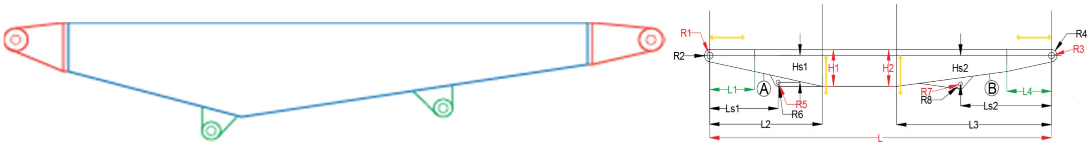


Figure 3.34 Different forms of assembling

4 Case study

Modern CAD systems with Product Life Management (PLM) support provide a virtual working environment in which the product's model is designed and manipulated. Using the geometric modelling capabilities, the engineer conceives, models, adds, deforms and edits the product's parts. The 3D virtual CAD model is accompanied by mathematical description, parameters, constraints and these can be modified and influence the future product design at any modelling phase, can be tested in various ways etc., which is a major advantage over the classic modelling systems.

We have proposed a parametric design method of the marine crane's mechanical part. That crane's mechanical model is used for our VCP project. That model is mainly used for crane's concept design phrase. In this chapter we will test how to convert a real product into a parametric model and how to use the parametric model with different requirements of working area and load.

The following cases will be tested in the NX. Siemens NX software is an integrated product design, engineering and manufacturing solution that helps the operator deliver better products faster and more efficiently. And NX has the similar interface and operation with other modern 3D CAD software. So it has a representative for testing in the NX.

4.1 Converting into parametric model

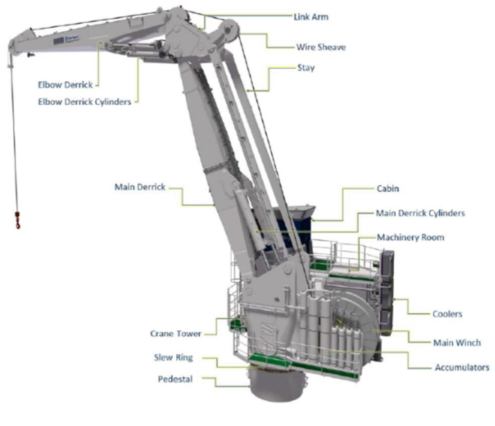


Figure 4.1 One type of crane

We take one type of knuckle boom crane for example to test the parametric design method. Now we will convert this model into a parametric model in the NX.

4.1.1 Simplify the crane

First the real marine crane product’s frame is too complicated and we will simplify its frame. We only care about the main structure of the crane so we remove non structure parts such as cabin, winch, and accumulators, like the figure 4.2 showed.

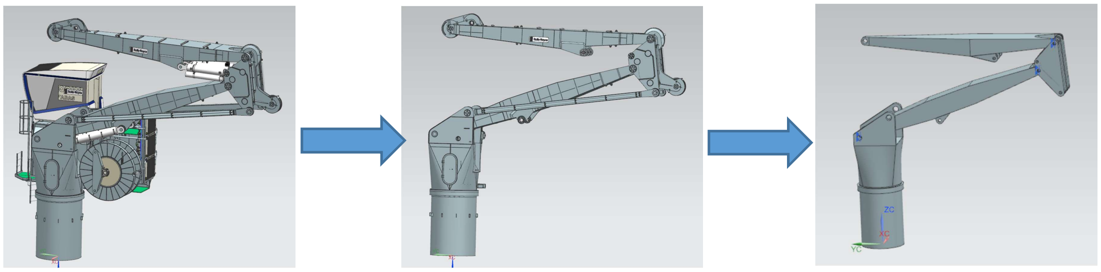


Figure 4.2 Simplify the crane

4.1.2 Abstract the main parameters

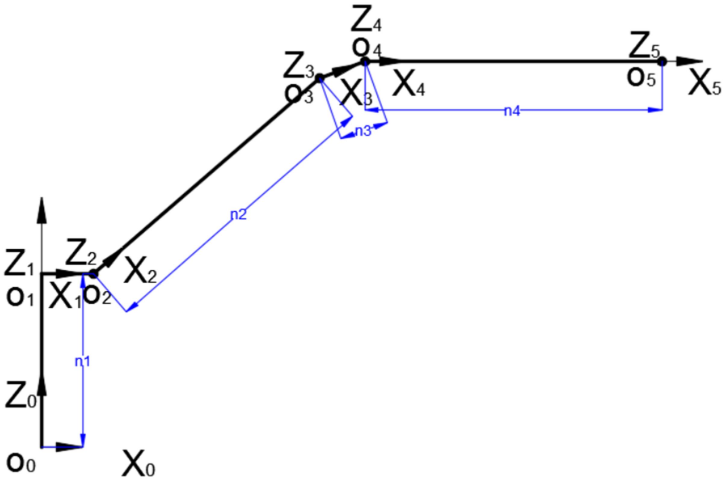


Figure 4.3 Kinematic model of the crane

Figure 4.3 is the kinematic model of the crane. n_1, n_2, n_3, n_4 are lengths of the each part and they are the main parameters.

With the kinematic model we can get the D-H table as follows:

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	n_1	Θ_1
2	90	b	0	Θ_2
3	0	n_2	0	Θ_3
4	0	n_3	0	Θ_4
5	0	n_4	0	0

Table 4.1 D-H table

Forward transformation matrix:

$$ {}_5^0T = {}_1^0T \cdot {}_2^1T \cdot {}_3^2T \cdot {}_4^3T \cdot {}_5^4T $$

$$ = \begin{bmatrix} c\theta_1 & -s\theta_1 & 0 & 0 \\ s\theta_1 & c\theta_1 & 0 & 0 \\ 0 & 0 & 1 & n_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} c\theta_2 & -s\theta_2 & 0 & b \\ 0 & 0 & -1 & 0 \\ s\theta_2 & c\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} c\theta_3 & -s\theta_3 & 0 & n_2 \\ s\theta_3 & c\theta_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} c\theta_4 & -s\theta_4 & 0 & n_3 \\ s\theta_4 & c\theta_4 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & n_4 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ = \begin{bmatrix} c\theta_1 c(\theta_2+\theta_3+\theta_4) & -c\theta_1 s(\theta_2+\theta_3+\theta_4) & s\theta_1 & c\theta_1[b+n_2c\theta_2+n_3c(\theta_2+\theta_3)+n_4c(\theta_2+\theta_3+\theta_4)] \\ s\theta_1 c(\theta_2+\theta_3+\theta_4) & -s\theta_1 s(\theta_2+\theta_3+\theta_4) & -c\theta_1 & s\theta_1[b+n_2c\theta_2+n_3c(\theta_2+\theta_3)+n_4c(\theta_2+\theta_3+\theta_4)] \\ s(\theta_2+\theta_3+\theta_4) & c(\theta_2+\theta_3+\theta_4) & 0 & n_1+n_2s\theta_2+n_3s(\theta_2+\theta_3)+n_4s(\theta_2+\theta_3+\theta_4) \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Jocobians:

$$ J = \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} \\ r_{21} & r_{22} & r_{23} & r_{24} \\ r_{31} & r_{32} & r_{33} & r_{34} \end{bmatrix} $$

$r_{11}=-s\theta_1[b+n_2c\theta_2+n_3c(\theta_2+\theta_3)+n_4c(\theta_2+\theta_3+\theta_4)]$;

$r_{12}=-c\theta_1[n_2s\theta_2+n_3s(\theta_2+\theta_3)+n_4s(\theta_2+\theta_3+\theta_4)]$;

$r_{13}=-c\theta_1[n_3s(\theta_2+\theta_3)+n_4s(\theta_2+\theta_3+\theta_4)]$;

$r_{14}=-c\theta_1[n_4s(\theta_2+\theta_3+\theta_4)]$;

$r_{21}=c\theta_1[b+n_2c\theta_2+n_3c(\theta_2+\theta_3)+n_4c(\theta_2+\theta_3+\theta_4)]$;

$r_{22}=-s\theta_1[n_2s\theta_2+n_3s(\theta_2+\theta_3)+n_4s(\theta_2+\theta_3+\theta_4)]$;

$r_{23}=-s\theta_1[n_3s(\theta_2+\theta_3)+n_4s(\theta_2+\theta_3+\theta_4)]$;

$r_{24}=-s\theta_1[n_4s(\theta_2+\theta_3+\theta_4)]$;

$r_{31}=0$;

$r_{32}=n_2c\theta_2+n_3c\ (\theta_2+\theta_3)\ +n_4c\ (\theta_2+\theta_3+\theta_4)$;

$r_{33}=n_3c\ (\theta_2+\theta_3)\ +n_4c\ (\theta_2+\theta_3+\theta_4)$;

$r_{34}=n_4c\ (\theta_2+\theta_3+\theta_4)$;

$$ \tau = J^T \cdot F $$

τ is the moment matrix in each joint;

J is the Jacobians and it could be got from D-H table;

F is the load force matrix at the end of the crane's terminal tip.

From the above equation we get the moments in each joint at any given position under certain load condition, then according to the cylinder support position the designer can get the force needed in the cylinder, and that will be talked later.

The values of n_i are as follows:

	n_1	n_2	n_3	n_4
mm	6000	11400	1800	11300

Table 4.2 Main parameters

4.1.3 Abstract the part parameters

1. Base

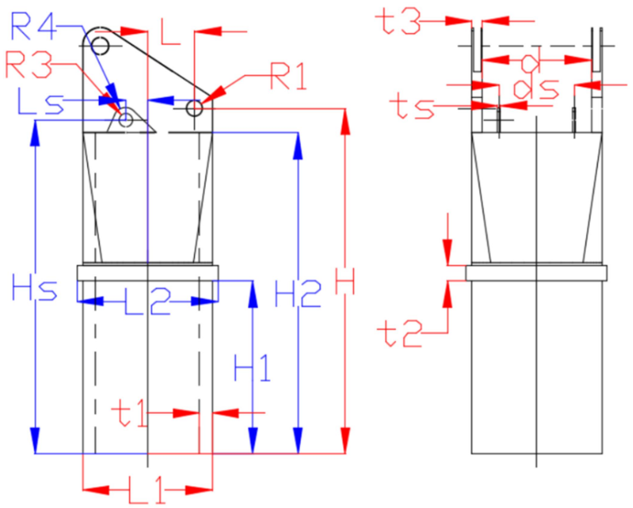


Figure 4.4 The sketch of the base

The sketch of the base is showed like figure 4.4. The values for each parameter are in the following table.

Main parameter(mm)	Secondary parameters	
	Independent parameters(mm) (set a default value by designer)	Coupling parameters(mm)
H=6000	$t_1=60$; $t_2=290$; $t_3=200$; $L_1=2485$; $d=2085$; $d_s=1140$; $t_s=60$; $R_1=150$; $R_3=165$;	$H_1=0.5\times H=3000$; $H_2= H_1+t_2+1600=4890$; $H_s=H_2+ 400=5290$; $L=L_1/2-80=1162.5$; $L_s=L_1/2-600=642.5$; $R_4=R_3+55=220$;

Table 4.3 Parameters in base

2. Link_1

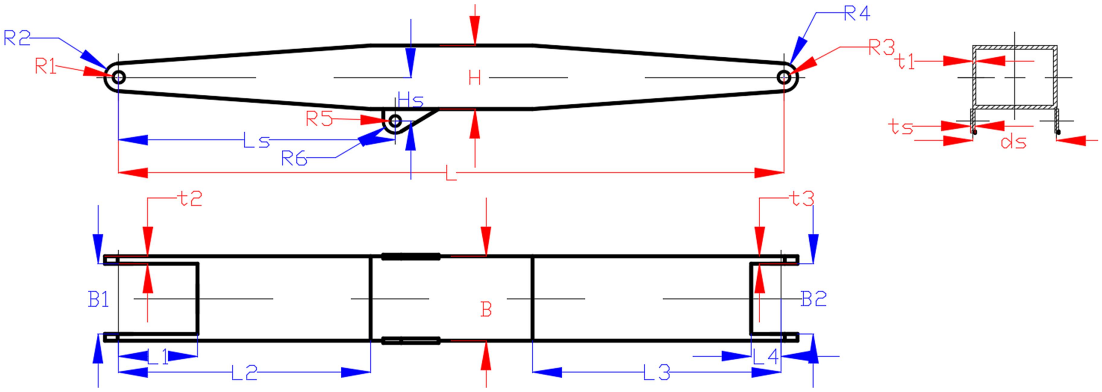


Figure 4.5 The sketch of link_1

The sketch of the link_1 is showed like figure 4.5. The values for each parameter are in the following table.

Main parameter (mm)	Secondary parameters	
	Independent parameters(mm) (set a default value by designer)	Coupling parameters(mm)
L=11400	H=1100; B=1450; t_1=60; t_2=120; t_3=120; t_s=70; R_1=100; R_3=100; R_5=90; d_s=1440;	$L_1=0.4\times L_2=1824$; $L_2=0.4\times L=4560$; $L_3=0.45\times L=5130$; $L_4=0.2\times L_3=1026$: $L_s=L_2+300=4860$; $Hs=H/2+200=750$; $B_1=B-2\times t_2=1210$; $B_2=B-2\times t_3=1210$; $R_2=R_1+135=235$; $R_4=R_3+135=235$; $R_6=R_5+50=140$;

Table 4.4 Parameters in link_1

3. Link_3

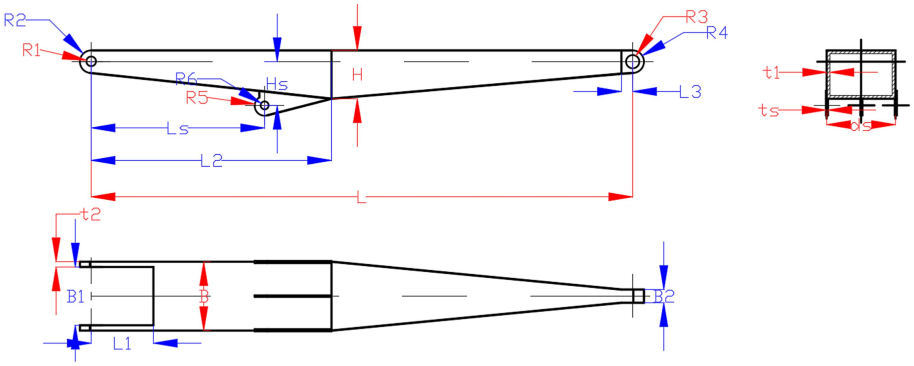


Figure 4.6 The sketch of link_3

The sketch of the link_3 is showed like figure 4.6. The values for each parameter are in the following table.

Main parameter (mm)	Secondary parameters	
	Independent parameters(mm) (set a default value by designer)	Coupling parameters(mm)
L=11300	H=1000; B=1450; t_1=60; t_2=120; t_s=40; R_1=100; R_3=140; R_5=80; d_s=1440;	$L_1=0.2\times L_2=1021.5$; $L_2=0.45\times L=5107.5$; $L_3=R_4=235$; $L_s=L_2-1402=3705.5$; $Hs=Ls\times(H-R2)/L2+354=920$; $B_1=B-2\times t_2=1210$; $B_2=0.2\times B=290$; $R_2=R_1+135=235$; $R_4=R_3+135=235$; $R_6=R_5+50=130$;

Table 4.5 Parameters in link_3

4. Link_2

Link_2's frame is different from other links. As for the parts in our library it's a nonstandard part.

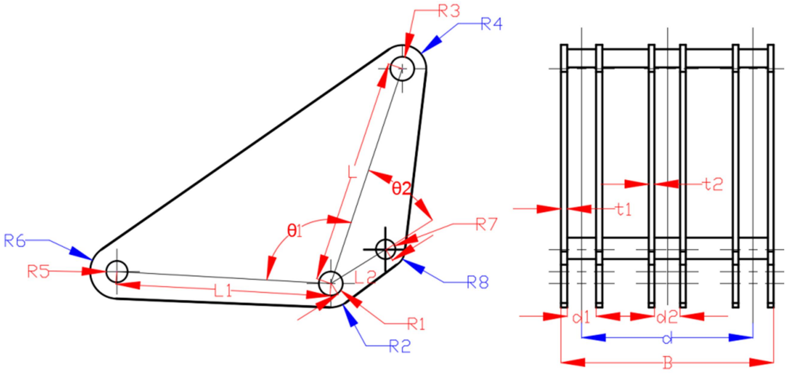


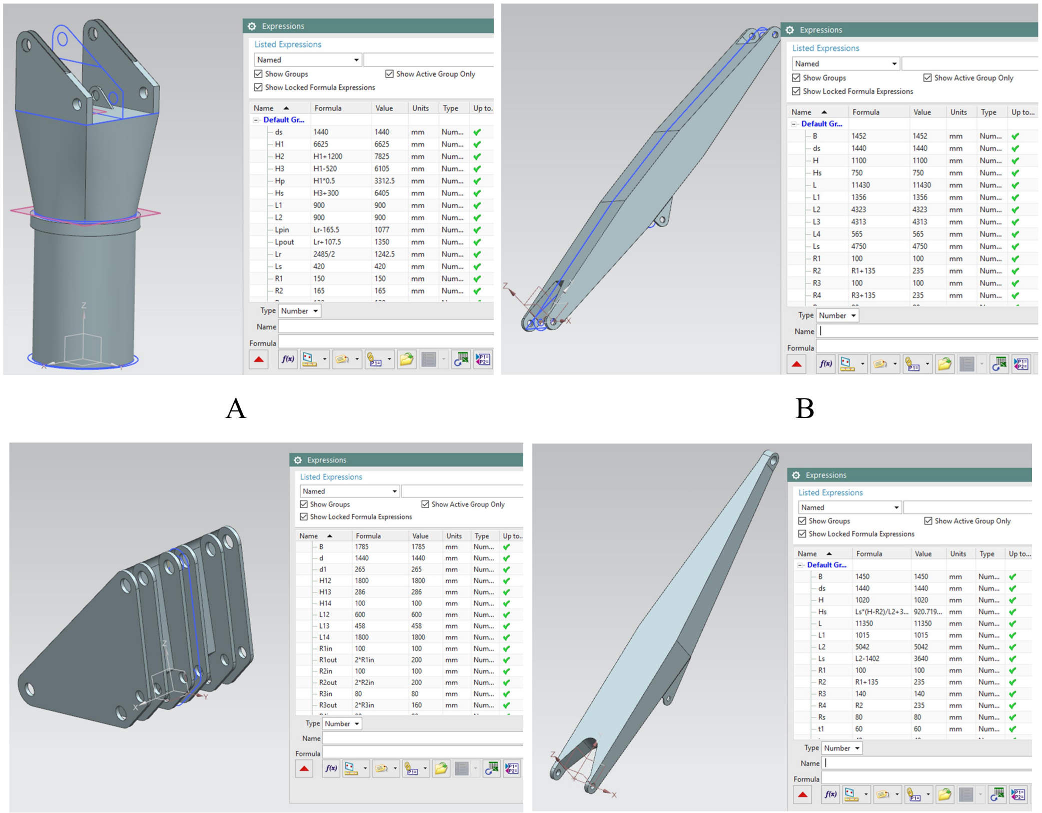
Figure 4.7 The sketch of link_2

The sketch of the link_2 is showed like figure 4.7. The values for each parameter are in the following table.

Main parameter (mm)	Secondary parameters	
	Independent parameters(mm) (set a default value by designer)	Coupling parameters(mm)
L=1800	L_1=1520; L_2=540; Θ_1=105°; Θ_2=40°; B=1785; t_1=50; t_2=50; R_1=100; R_3=100; R_5=90; R_7=80; d_1=245; d_2=215;	d=B-2×t_1-d_1=1440; R_2=2× R_1=200; R_4=2× R_2=200; R_6=2× R_5=180; R_8=5× R_5/2=200;

Table 4.6 Parameters in link_2

4.1.4 Creating models in NX and assembling



A

Expressions

Listed Expressions

Named

☑ Show Groups ☑ Show Active Group Only

☑ Show Locked Formula Expressions

Name	Formula	Value	Units	Type	Up to...
Default Gr...					
ds	1440	1440	mm	Num...	✓
H1	6625	6625	mm	Num...	✓
H2	H1+1200	7825	mm	Num...	✓
H3	H1-520	6105	mm	Num...	✓
Hp	H1*0.5	3312.5	mm	Num...	✓
Hs	H3+300	6405	mm	Num...	✓
L1	900	900	mm	Num...	✓
L2	900	900	mm	Num...	✓
Lpin	Lr-165.5	1077	mm	Num...	✓
Lpout	Lr+107.5	1350	mm	Num...	✓
Lr	2485/2	1242.5	mm	Num...	✓
Ls	420	420	mm	Num...	✓
R1	150	150	mm	Num...	✓
R2	165	165	mm	Num...	✓

Type Number

B

Expressions

Listed Expressions

Named

☑ Show Groups ☑ Show Active Group Only

☑ Show Locked Formula Expressions

Name	Formula	Value	Units	Type	Up to...
Default Gr...					
B	1452	1452	mm	Num...	✓
ds	1440	1440	mm	Num...	✓
H	1100	1100	mm	Num...	✓
Hs	750	750	mm	Num...	✓
L	11430	11430	mm	Num...	✓
L1	1356	1356	mm	Num...	✓
L2	4323	4323	mm	Num...	✓
L3	4313	4313	mm	Num...	✓
L4	565	565	mm	Num...	✓
Ls	4750	4750	mm	Num...	✓
R1	100	100	mm	Num...	✓
R2	R1+135	235	mm	Num...	✓
R3	100	100	mm	Num...	✓
R4	R3+135	235	mm	Num...	✓

Type Number

C

Expressions

Listed Expressions

Named

☑ Show Groups ☑ Show Active Group Only

☑ Show Locked Formula Expressions

Name	Formula	Value	Units	Type	Up to...
B	1785	1785	mm	Num...	✓
d	1440	1440	mm	Num...	✓
d1	265	265	mm	Num...	✓
H12	1800	1800	mm	Num...	✓
H13	286	286	mm	Num...	✓
H14	100	100	mm	Num...	✓
L12	600	600	mm	Num...	✓
L13	458	458	mm	Num...	✓
L14	1800	1800	mm	Num...	✓
R1in	100	100	mm	Num...	✓
R1out	2*R1in	200	mm	Num...	✓
R2in	100	100	mm	Num...	✓
R2out	2*R2in	200	mm	Num...	✓
R3in	80	80	mm	Num...	✓
R3out	2*R3in	160	mm	Num...	✓

Type Number

D

Expressions

Listed Expressions

Named

☑ Show Groups ☑ Show Active Group Only

☑ Show Locked Formula Expressions

Name	Formula	Value	Units	Type	Up to...
Default Gr...					
B	1450	1450	mm	Num...	✓
ds	1440	1440	mm	Num...	✓
H	1020	1020	mm	Num...	✓
Hs	Ls*(H-R2)/L2+3...	920.719...	mm	Num...	✓
L	11350	11350	mm	Num...	✓
L1	1015	1015	mm	Num...	✓
L2	5042	5042	mm	Num...	✓
Ls	L2-1402	3640	mm	Num...	✓
R1	100	100	mm	Num...	✓
R2	R1+135	235	mm	Num...	✓
R3	140	140	mm	Num...	✓
R4	R2	235	mm	Num...	✓
Rs	80	80	mm	Num...	✓
t1	60	60	mm	Num...	✓

Type Number

Figure 4.8 The models in NX

With the parameters defined above, we could create each part model in the NX like the figure 4.8 showed. And the final assembled crane is like the following figure. During the assembling process, the parameters related fit between two parts can be also adjusted quickly and conveniently.

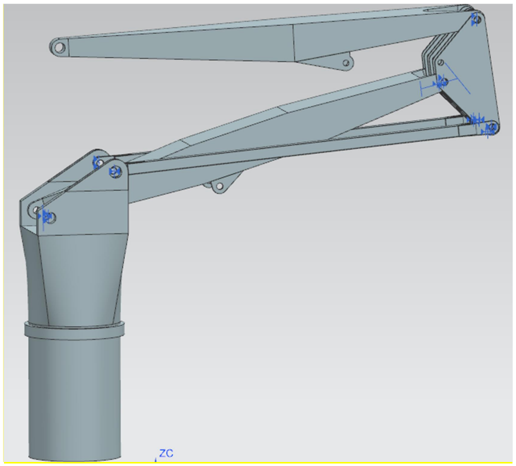


Figure 4.9 The assembled crane

4.2 Parametric model used in concept design

In the marine crane production, the products are often repeated the same or similar structure and used different sizes so that it can produce a series of products to meet different needs.

Now for example the crane got in the above section is a parent crane. If the working area and load are all reduced by half, how to use the parametric way generate a new model.

1. **Driving force determination**

From section 4.1.2 we have got an equation.

$$\tau = J^T \cdot F$$

$$\begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \end{bmatrix} = J^T \cdot \begin{bmatrix} 0 \\ 0 \\ G \end{bmatrix}$$

τ_1, τ_2, τ_3, τ_4 are the moments in each joints;
J^T is the transposed matrix of Jocobians;
G is the gravity of the working load.

If the working area and load are both reduced by half, we can get the new values of moments on each joint by calculating. Then we can get the force needed on the driven cylinder through simple geometry calculation. According to the force value the designer can choose the proper hydraulic cylinder.

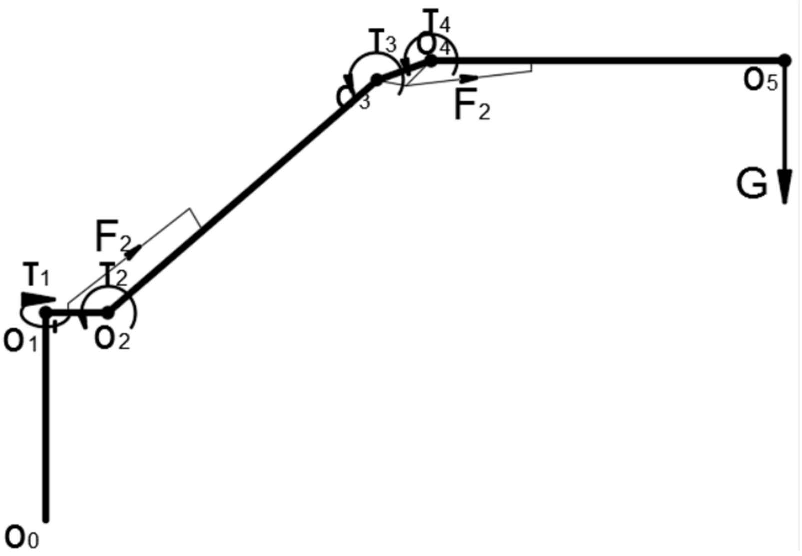


Figure 4.10 Skeleton model of the crane

2. Geometry determination

From the above part, the length of each part has been determined. According to the parent crane's part lengths which have been marked in the section 4.1.2, the new crane's part lengths are in following table.

	n_1	n_2	n_3	n_4
mm	5000	9000	1200	8000

Table 4.7 Main parameters

When doing the concept design in parametric design method, we assume that each part is rigid. So we don't do the strength checking calculation.

The main parameters are decided with the working area, and the secondary parameters will be decided according to the designer's experience. The figure 4.11 shows the parent crane and the new crane which working area and load are half of the parent crane.

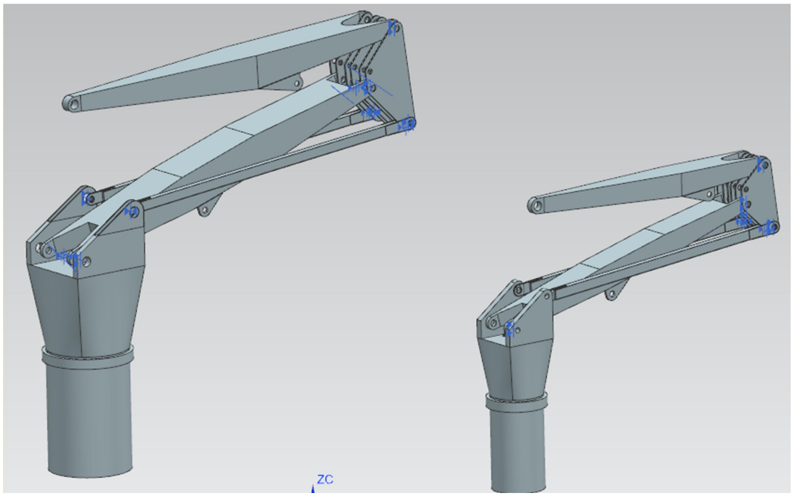
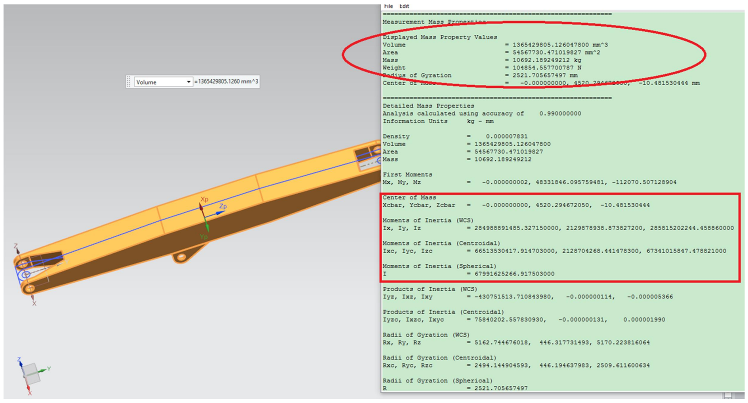


Figure 4.11 The parent crane and new crane

When the model is finished, the designer using current CAD software to create 3D model could get the mass, weight, centre of the mass and the moments of inertia like the figure 4.12 showed. Those values could be used in the statics and kinematics calculations. Maybe the creating model is not accurate, but it could be as a reference. And parameters in our design method included the parts length, width, height and thickness which have great effected on the calculations could be adjusted timely and conveniently.



```
=============================================================
Measurement Mass Properties

Displayed Mass Property Values
Volume                          = 1365429805.126047800 mm^3
Area                            = 54567730.471019827 mm^2
Mass                            = 10692.189249212 kg
Weight                          = 104854.557700787 N
Radius of Gyration              = 2521.705657497 mm
Center of Mass                  =   -0.000000000, 4520.294672050,  -10.481530444 mm

=============================================================
Detailed Mass Properties
Analysis calculated using accuracy of    0.990000000
Information Units     kg - mm

Density               =    0.000007831
Volume                = 1365429805.126047800
Area                  = 54567730.471019827
Mass                  = 10692.189249212

First Moments
Mx, My, Mz            =   -0.000000002, 48331846.095759481, -112070.507128904

Center of Mass
Xcbar, Ycbar, Zcbar   =   -0.000000000, 4520.294672050,  -10.481530444

Moments of Inertia (WCS)
Ix, Iy, Iz            = 284988891485.327150000, 2129878938.873827200, 285815202244.458860000

Moments of Inertia (Centroidal)
Ixc, Iyc, Izc         = 66513530417.914703000, 2128704268.441478300, 67341015847.478821000

Moments of Inertia (Spherical)
I                     = 67991625266.917503000

Products of Inertia (WCS)
Iyz, Ixz, Ixy         = -430751513.710843980,   -0.000000114,   -0.000005366

Products of Inertia (Centroidal)
Iyzc, Ixzc, Ixyc      = 75840202.557830930,   -0.000000131,    0.000001990

Radii of Gyration (WCS)
Rx, Ry, Rz            = 5162.744676018,  446.317731493, 5170.223816064

Radii of Gyration (Centroidal)
Rxc, Ryc, Rzc         = 2494.144904593,  446.194637983, 2509.611600634

Radii of Gyration (Spherical)
R                     = 2521.705657497
```

Figure 4.12 Some information about the part

4.3 Solution for general marine cranes

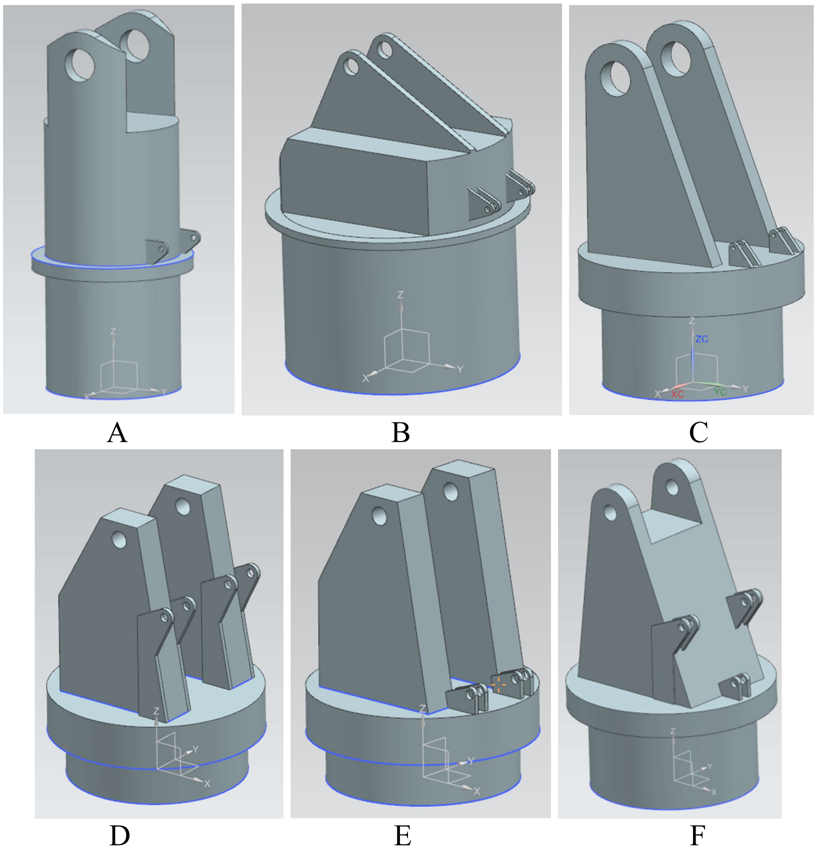
The crane discussed above is a non-standard one and its patent belongs to one famous company. Although that crane's frame is not representative, we still approve that it can be changed into parametric model. The most common used cranes on board have the simple shapes and they have the similar frames. Therefore we can create a part library and from the library the designer can choose the parts according to the crane's type to assemble a crane model. That will make the crane's concept design more efficient.

In the section 3.2 we have discussed the principle of the library creating. Now we will directly use the results got by section 3.2. Like the figure 3.5 showed, the library has divided into two layers, basic components layer and parts layer. Basic components will be assembled into different parts and different parts will be assembled into different type of crane.

We still use NX as a tool to create a library for example. In the section 3.3.5, when talking about the "Getting the geometric model" we have said that the realization of the assembly could be in varied forms. Considering the ease of operation in the NX, we will integrate the basic components layer into the parts layer; as for different combination of joint, link and support, it will be created a single model for each type of part. So in the library created in NX, it will be only showed in the form of part library.

The part library contains 3 parts, base, link_n-1and link_n.

Base:

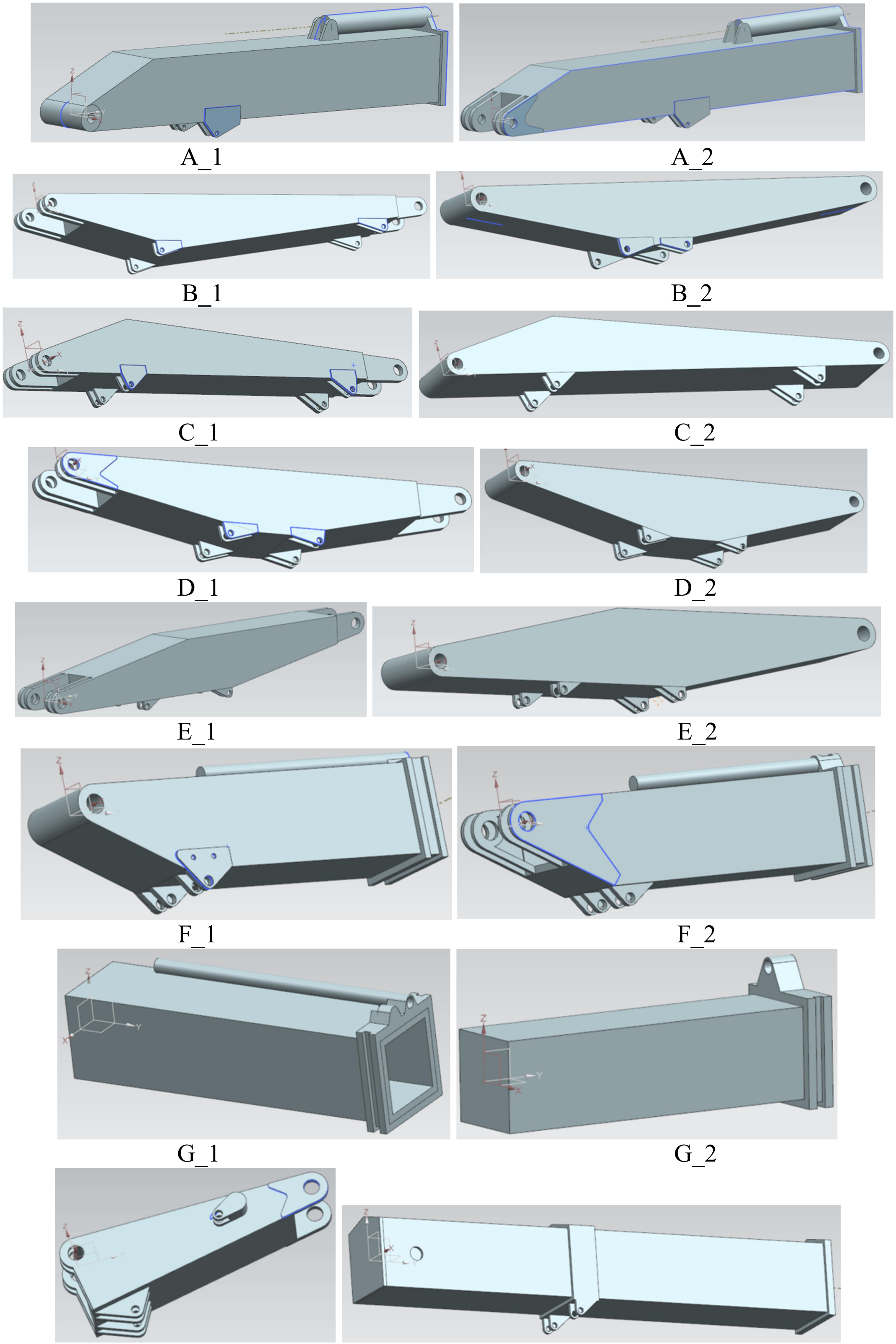


A B C

D E F

Figure 4.13 Different types of bases

Link_n-1:



A_1 A_2

B_1 B_2

C_1 C_2

D_1 D_2

E_1 E_2

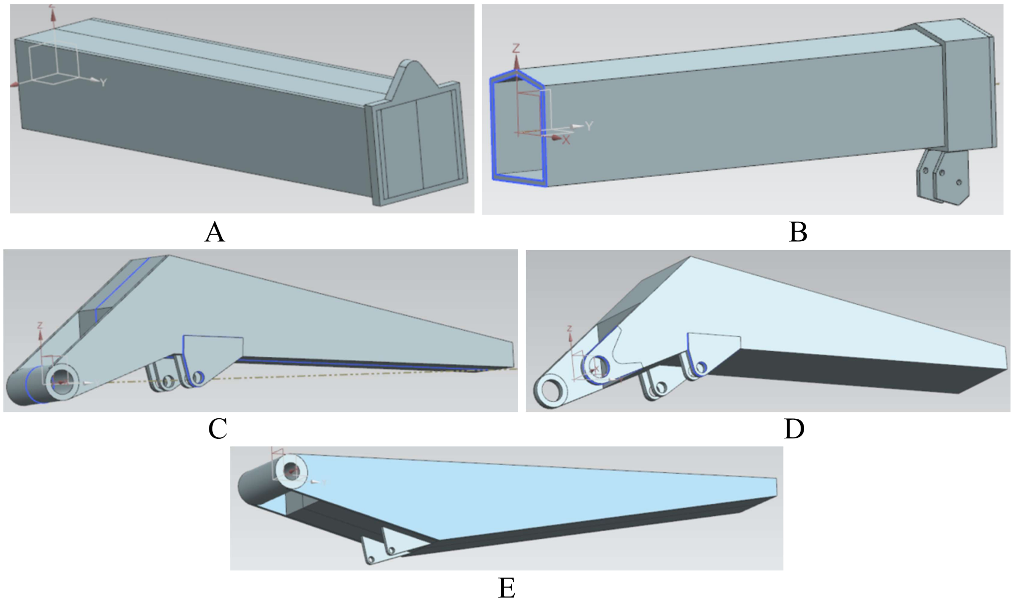
F_1 F_2

G_1 G_2

H_1 H_2

Figure 4.14 Different types of link_n-1

Link_n:


A

B

C

D

E

Figure 4.15 Different types of link_n

All the parameters used in creating above parts are set arbitrarily by designers at first. There are so many types of the marine cranes on the ship. In our library we try our best to include all those crane's parts. With the development of the technology, new type cranes will be always invented and new part's frame may appear. So the part library is opened. The designer can add any new frame parts to abound parts in the library.

Now we assume that we need a crane which has the following requirement.

Outreach(m)	Lifting height(m)	Load(Te)
3~10	3~ 10	10

Table 4.8 Initial condition

1. According to the requirement of working area, the designer can decide the numbers of the link and the main parameters for each part.

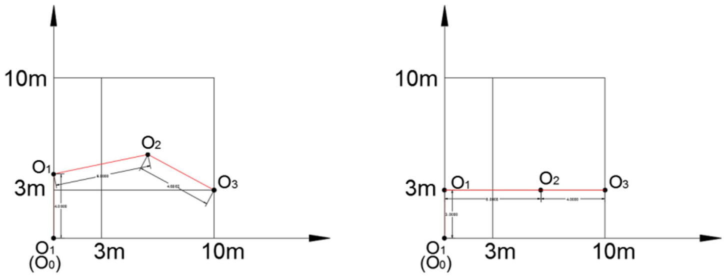


Figure 4.16 The main parameters for two types of crane

In this case, to meet working area, many kinds of crane can be used. We just take a knuckle boom crane and telescopic boom crane for example. The main parameters of the two types' cranes are as follows:

Main parameters	n1(m)	n2(m)	n3(m)
Knuckle boom crane	4	6	4.68
Telescopic boom crane	3	6	4

Table 4.9 Main parameters in different types of crane

2. Once the numbers of the link and the main parameters decided, the kinematic models can be created.

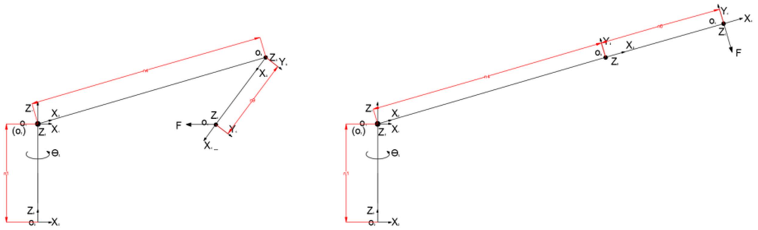


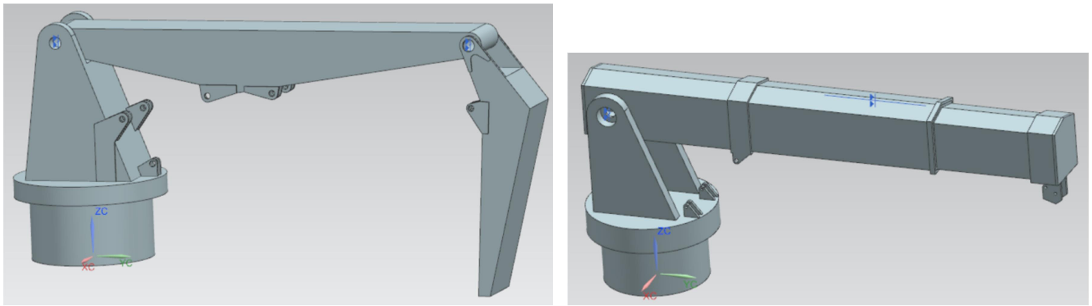
Figure 4.17 Kinematic models

With the kinematic models, the designer can calculate the actuators' forces. The calculation method is followed the section 2.2.

3. With the crane's type, the designer can use the parts form the library to assemble the crane. Then changing each part main parameters into the ones decided in the step1.

4. With the designer's experience, the designer can adjust the secondary parameters of each part to make the crane meet certain proportion.

5. Got the crane.



A B

Figure 4.18 Different types of crane

4.4 Summary

From the above case, we can see that the concept design for general marine crane is very convenience and fast with the using of the part library. And it also can support multiple choices for designers' finial decisions. It approves that creating parts library in advance makes doing the concept design for general marine cranes more efficiently. Because all the parts in the library are parametric models, they can be easily changed length, width, height and thickness.

Combined with section 4.2, every type of crane can easily generate a series of prototypes which have similar shapes but different dimensions.

No matter whatever situation we met, the design process will always follow the steps like the figure 4.19 showed. Generally, before the designing the initial condition has been given, working area and working load. According to the working area, the designer can decide the main parameters, then with the main parameters the kinematic model could be created, and combined with the working load, the driving torque could be got; With the designer's experiences the secondary parameters can be decided by the designer; the parts models could be created by using main parameters and secondary parameters then they can be assembled into a crane's model. The crane's model and the driving torque will be the output for the following use.

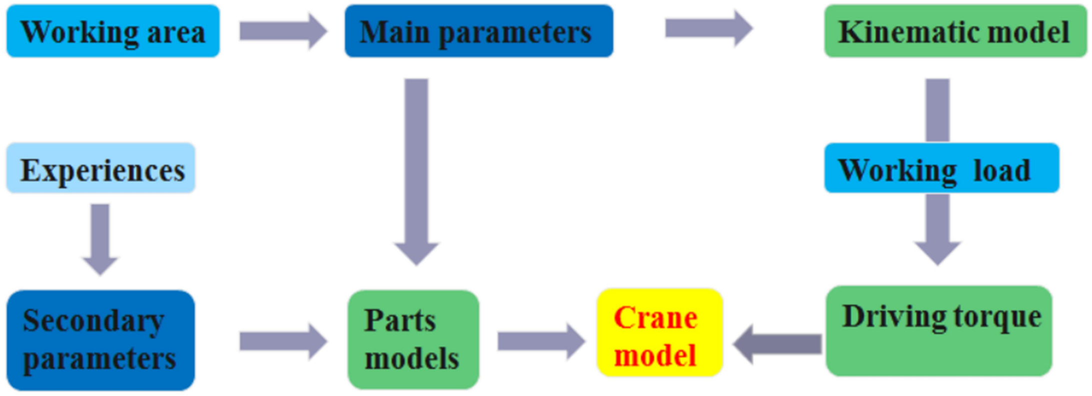


Figure 4.19 The design process flow chat

After testing, we find that no matter using the part library to create the crane model or changing a parent crane into a new one, using parametric way to do the designing will obviously reduce the operation steps, save the half time compared to the traditional approach at least and increase the efficiency for the concept design. So the parametric mechanical design is feasible and useful for the VCP.

The virtual prototyping in other fields, such as auto industry and aviation industry, is mainly based on the system's mathematical expression and lack of intuitive manifestation. And that requires the designer must be very professional. In VCP, the modelling of the mechanical part could be done by the “amateur”. Although it also includes the crane’s kinematics mathematical expression, the simulation results could be showed directly to the designer in 3D animation combing the mechanical part model and it also provide a useful tool for crane’s concept design. So the virtual prototyping in VCP is more intuitive and easier to operate.

5 Conclusion and future work

In this report a parametric mechanical design method for virtual crane has been proposed and tested. This parametric mechanical design method is originally to solve the modelling for the mechanical part of the Virtual Crane Project. That modelling for the mechanical part of the virtual crane is used for concept design and simulation. As originally conceived, we wish we could fine a design method for the mechanical part modelling simple, fast and efficient.

Contributions are as follows:

1. **Open mechanical parts modelling libraries**: open library of generic models of all key marine crane parts. According to the designer's different design habits and tools, the library can be consisted of key elements, joint, link and support, and it also can be consisted of key parts, base and different arms. Those two library creating ways both have pros and cons. Creating element library will make the components in the library less and creating part library could make the parameters output more easily. In the case study in this thesis, the part library has been used. This library is opened. The designer can add any new frame parts to abound parts in the library.
2. **Variant parametric design**: allow easy adjustment of geometric lengths, widths, heights and thicknesses for each crane's part. According to VCP's feature and machinery geometric modelling, the parameters decided the part's frame have been separated into main parameters and secondary parameters. If only focus on the crane's kinematics performance, the designer could only adjust main parameters. For the crane's concept design, the parametric model could be also adjusted easily with changing fewer parameters.
3. **Visual Demonstrations and feedback**: with graphical interface showing key features and results obtained (system metrics, charts) for specific cases and examples. The main parameters and independent parameters in secondary parameters of each part will be adjusted by the designer one by one. With some parameters output from the crane's model, loading chat and torques on the actuated joints could be got.

These findings lead to designing methods for mechanical part modelling can be simple, fast and efficient in cranes' modelling. This could benefit to mechanical design in conceptual ways rather than practical products. The research results will provide new tools for more efficient and more effective design and testing of marine crane systems.

In the part library, it could not be included all the crane's parts. With the development of marine crane industry new type of the crane will be produced. So the library's completion is never ended. And in this thesis we only discuss the 3 type of cranes, other types such as A frame crane and lattice boom crane are not talked about. In the case study, we only use a kind of CAD software, NX, to test the design method. How it will be used with programming method hasn't been tested. So adding new shapes' parts, parameterizing other types of crane and testing the parametric mechanical design method by using program languages need to be investigated in the future. And making the layouts of the graphical interface for parameters input and output more intuitive and fool-operational also should be discussed.

Reference

[1] Skejic, R. & Faltinsen, O. (2008). A unified seakeeping and maneuvering analysis of ships in regular waves. Journal of Marine Science and Technology, 13, 371-394.

[2] Lotter, B. (1986). Manufacturing Assembly Handbook. Boston, USA: ButterworthHeinemann.

[3] Kozak, J.J., Hancock, P.A., Arthur, E.J. and Chrysler, S.T. "Transfer of training from virtual reality" Ergonomics, 1993, Vol 36, No.7, 777–784Matlab. Wavelet Toolbox. Users Guide. The Math Works Inc., 1997.

[4] G.Gary wang."Definition and Review of Virtual Prototyping". J. Comput. Inf. Sci. Eng 2(3), 232-236 (Jan 02, 2003) (5 pages).

[5] Alkass, S, Alhussein, M and Moselhi, O (1997) Computerized crane selection for construction projects. In: Stephenson, P (Ed.), 13th Annual ARCOM Conference, 15-17 September 1997, King's College, Cambridge. Association of Researchers in Construction Management, Vol. 2, 427-36. Wei-Jung Shang, Cannon, D., Gorman, J.. "Dynamic analysis of the cable array robotic crane". IEEE International Conference, 1999.Vol 4, 2495-2500.

[6] Sehyun Myung, Soonhung Han. Knowledge-based parametric design of mechanical products based on configuration design method. Expert Systems with Applications.Volume 21, Issue 2, August 2001, Pages 99–107.

[7] Monedero, J (2000). Parametric design: a review and some experiences. Automation in Construction Vol 9 No 4 pp 369-377.

[8] http://www.km.kongsberg.com/ks/web/nokbg0240.nsf/AllWeb/9F7755D6A9A7CE32C1257AAE005389F6?OpenDocument.

[9] Shah, J. J.,& Rogers,M. T. (1993). Assembly modelling as an extension of feature-based design. Research in Engineering Design, 5(3–4), 218-237.

[10] Karinthi, R. R., & Nau, D. (1992). An algebraic approach to feature interactions. IEEE Transactions on Pattern Analysis and Machine Intelligence, 14(4), 469–484.

[11] Faheem,W., Hayes, C. C., Castano, J. F.,& Gaines, D.M. (1998).What is a manufacturing interaction? In Proceedings of the 1998 ASME Design Engineering Technical Conferences.

[12] Regli, W. C., & Pratt, M. J. (1996). What are feature interactions? In Proceedings of the 1996 ASME Design Engineering Technical Conference and Computers in Engineering Conference.

[13] Feng, C. X., Huang, C. C., Kusiak, A., & Li, P. G. (1996). Representation of functions and features in detail design. Computer-Aided Design, 28(12), 961–971.

[14] Mukherjee, A., & Liu, C. R. (1997). Conceptual design, manufacturability evaluation and preliminary process planning using function-form relationships in stamped metal parts. Robotics & Computer-Integrated Manufacturing, 13(3), 253–270.

[15] G. Sunde, V. Kallevik, A dimension driven CAD system utilizing AI techniques in CAD. Report no. 860216-1, Senter for Industriforskning, 1987.

[16] Khoshnevis, B., Sormaz, D. N., & Park, J. Y. (1999). An integrated process planning system using feature reasoning and space search-based optimization. IIE Transactions, 31(7), 597–616.

[17] https://www.fmi-standard.org/

[18] Alexander, C., Notes On The Synthesis of Form, Harvard University Press, Cambridge, Massachusetts, 1964.

[19] Freeman, P. and Newell, A., A Model for Functional Reasoning in Design, proc. 2nd IJCAI, London, pp. 621–640, 1971.

[20] Yashikawa, H., Introduction to General Design Theory, in Intelligent Manufacturing Systems I, V.R. MilaV Ci´ C (ed.), pp. 3–17, Elsevier Science Publishers B.V., Amsterdam, 1988.

[21] Ghionea, I., (2013), Stude of computer aided design and simulation importance in the conception and development phases of a product. Proceedings of the IMC 2013 International Multidisciplinary Conference, 22-24 may, Technical University of Cluj Napoca, North University Center of Baia Mare România – University College of Nyiregyhaza Hungary. pp.55-58. Bessenyei Publishing House, ISBN 978-615-5097-66-9.

[22] Budynas, R., Nisbett, K. Shigley, J. E., (2011), Mechanical Engineering Design. McGraw-Hill, ISBN 978-007-3529-28-8, United States of America.

[23] Koichi Kondo, PIGMOD: parametric and interactive geometric modeller for mechanical design. Computer-Aided Design 22(10): 633-644 (1990).

[24] Salomon, D., (2006), Curves and Surfaces for Computer Graphics. Northridge, U.S.A. Springer.

[25] Weisberg, D., (2008), The Engineering Design Revolution, on-line book.

[26] Denavit, Jacques; Hartenberg, Richard Scheunemann (1955). "A kinematic notation for lower-pair mechanisms based on matrices". Trans ASME J. Appl. Mech 23: 215–221.

[27] Hartenberg, Richard Scheunemann; Denavit, Jacques (1965). Kinematic synthesis of linkages. McGraw-Hill series in mechanical engineering. New York: McGraw-Hill. p.435.

[28] J.S. Milne (1986), "Jacobian Varieties", Arithmetic Geometry, New York: Springer-Verlag, pp. 167–212, ISBN 0-387-96311-1.