



**NAZARBAYEV
UNIVERSITY**

School of Engineering & Digital Sciences

**Bachelor of Engineering in
Mechanical and Aerospace Engineering**

**Static Mechanical Design of the Dinosaur Carcass for
Display**

ENG 400: Capstone project

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April, 2025

Declaration

We hereby declare that this report entitled “Static Mechanical Design of the Dinosaur Carcass for Display” is the result of our own project work except for quotations and citations that have been duly acknowledged. We also declare that it has not been previously or concurrently submitted for any other degree at Nazarbayev University.

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Acknowledgements

Gulnur Muratova, a graduate in Eurasian Studies, is acknowledged for her role in initiating this project and for presenting it to the Deans of the School of Mining and Geosciences (SMG) and the School of Engineering and Digital Sciences (SEDS).

Acknowledgement is due to Dias Kadirbek, a graduate in Geoscience, who is currently working on the reconstruction of the skeleton and has provided access to the necessary bone samples.

Appreciation is also given to Albert Pshennikov and Andrei Iankin, laboratory assistants, for their invaluable support in learning the process of 3D scanning using ZEISS T-SCAN technology.

Acknowledgements to Rustam Askaruly - senior manager of FABLAB - for providing access to the necessary equipment.

Acknowledgements to Daniya Baizhanova and Aida Istleliyeva - students of NU - who volunteered to help during the assembly process with the placement of the phalanges of the paddles with a reference to the existing skeletons of the ichthyosaurs.

Abstract

The bones of Ichthyosaurs excavated on the territory of Kazakhstan in 2018 are kept at Nazarbayev University. Currently, they are unavailable for public display. The current work is dedicated to creating a 3D model of the available bones in an effort of creating a model of the full Ichthyosaurus to be displayed. After considering different methods of scanning and printing, the choice was set to ZEISS T-SCAN scanning technology to create a digital model of the bones and the FDM printing method with PLA+ filament. The choice is explained by a consideration of the availability of devices, the time the model was projected to take, and the quality of the produced models. The digital versions of the bones also went through a structural analysis for considerations of the appropriate assembling mechanisms using CAD-format softwares. The skeleton was 3D printed by using PLA+ filament in color “bone white” on Bambu Lab X1E printer. The bones were assembled into a full skeleton through metal wire and reinforcement. The metal framework was used to hang the skeleton, and nylon steel based metal alloy cables and construction lines were used as supports that hold the structure together. Overall, the aim of the project was met and the dinosaur carcass for display was prepared.

Abbreviations

ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
ANSYS	Analysis of Systems
ASA	Acrylonitrile Styrene Acrylate
BVOH	Butanediol Vinyl Alcohol Copolymer
CAD	Computer Aided Design
CMM	Coordinate Measuring Machine
CPE	Chlorinated polyethylene
CT	Computerized Tomography
DICOM	Digital Imaging and Communications in Medicine
FDM	Fused Deposition Modelling
IGS	Initial Graphics Exchange Specification
LiDAR	Light Detection and Ranging
PA	Polyamide
PBF	Powder Bed Fusion
PC	Polycarbonate
PET	Polyethylene Terephthalate
PETG	Polyethylene Terephthalate Glycol
PLA	Polylactic Acid
PP	Polypropylene
PPA-CF/GF	Premium Fiber/Glass Fiber-Reinforced Nylon
PPS	Polyphenylene Sulfide
PVA	Polyvinyl Alcohol
SL/SLA/STL	Stereolithography
SLS	Selective Laser Sintering

TPU

Thermoplastic Polyurethane

UCLH

University College London Hospitals

UV

Ultra Violet

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1. Introduction

1.1. Brief History of the Ichthyosaur

Ichthyosaurs were sea reptiles that lived in the Mesozoic era, Late Jurassic period, about 145-200 million years ago. As can be seen from Fig.1.1, these streamlined, dolphin-like creatures were highly specialized for aquatic life, with features such as a torpedo-shaped body, large eyes adapted for deep-sea vision, and limbs modified into flippers [1]. There were at least 80 species of ichthyosaurs, which had different sizes, ranging from a few feet to up to 15 meters [2].

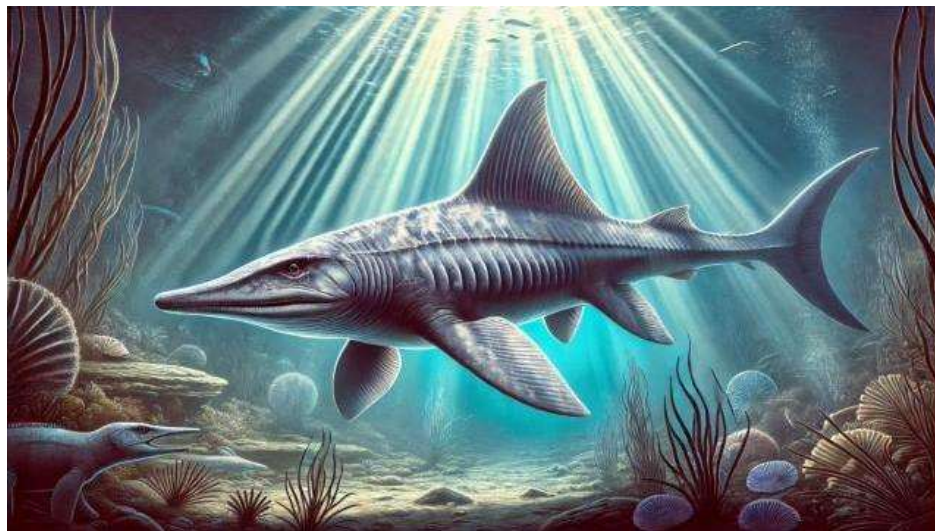


Figure 1.1: Restored picture of the ichthyosaur [3]

In 2018, a school organization called “Zhas Geolog” found the bones of the previously unknown ichthyosaur, with a length of more than 10 meters [3]. The excavations were done in West Kazakhstan, Bayterek region, near Talovaya River valley, 1.5 km from the former village of Shchuchkino (see Fig.1.2) [4-6]. Hence, the dinosaur was given the name of *Kazakhstanosaurus Shchukinensis*. The *Nannopterygius* genus was assigned to this species due to the different structure of the forelimb, main occipital bone, and main sphenoid bone [4].



Figure 1.2: Location of the ichthyosaur skeleton fragments in West Kazakhstan [4]

The excavation was led by Dr. Efimov, a scientist from the Ulyanovsk Paleontology Center, between 2016 and 2018 [5]. The bones were transported to Russia to be thoroughly described and then returned to Kazakhstan. The large-scale reconstruction project was started in 2021 by the late Dr. Laurent Richard, Associate Professor of the School of Mining and Geosciences at Nazarbayev University. Currently, there are 138 available bones for the replication process provided by the School of Mining and Geoscience.

1.2. Problem Statement

Nazarbayev University is in possession of the Ichthyosaur bones, however, they are not available for public display. The creation of a complete dinosaur model is necessary for the bones to be displayed.

There is no complete, ready-to-use method available for the creation of the model. The method requires a decision on scanning and printing devices, as well as the method as to how separate bones will be assembled into a model. The exhibition has to be stable and reflect the structure of the dinosaur well in three dimensions. The form, the weight, and the stress of the bones have to be considered for a decision on the joints for the model.

An additional problem is the condition of the bones: some of the available bones are deformed, and some of the bones necessary for a full model are missing. A full restoration entails that the model has to reconstruct the missing and damaged bones.

It should be mentioned that other species of dinosaurs like *Arstanosaurus Akkurganensis* from Kyzylorda Region, *Jaxartosaurus Aralensis* from South Kazakhstan region, *Batrachognathus Volans* from Karatau Jurassic lake, and more were found across Kazakhstan [7]. However, most of them were not presented in the museums since the making of the exhibit requires the intervention of specialists from abroad, namely the Paleontological Museum in Paris, the Natural History Museum of London, and Berlin [8]. Therefore, it is crucial to create standardized guidelines for designing a display of the dinosaur that can be used by local museums.

1.3. Aim and Objectives

The main aim of this work is to build a fully assembled Ichthyosaurus skeleton model. The objectives below outline the work that should be done in order to create the aforementioned model:

- To find the optimal methods for the creation of fossil exhibits as a guideline for future implementations
- To find the appropriate scanning and printing methods for the recreation of the separate bones
- To make an assembly of the Ichthyosaurus model as an exhibit to be put on display at the university, with consideration for the structural stability of the model
- To use 3D modeling for solving the issue of missing and damaged pieces, by surface analysis

This work will now turn to a literature review on the scanning and printing methods used in 3D-modelling in general and for the creation of fossil models in particular. It will then explain the selected methodology for the creation of the model that is based on the aforementioned literature. Then, the results and the discussion section will cover the existing progress as well as explain the work that is yet to be done.

2. Literature Review

2.1 Scanning techniques

The first steps in the replication of the skeleton involve the 3D scanning process, which collects the information of the real-world object on the shape, geometry and dimensions to create a digital model for further usage. The resulting data is point cloud data that is obtained by the usage of various types of 3D scanning technologies which include photogrammetry, CT scanning, laser scanning, structured light scanning, and contact-based scanning [8].

2.1.1 Photogrammetry

Photogrammetry is the method that uses a combination of photographic images, which will be processed by computer software with the help of algorithms such as the least squares method, to result in the reconstruction of the object with the shape, surface and color [9]. The photogrammetric method of 3D scanning works by the principle of taking several photographic images of the object from different viewpoints with consideration of reference points and creating the 3D model from these 2D images [10, 11]. One of the main aspects of the process is the grid, which is projected onto the item and used in the calculation of dimensions by the difference due to deformation [10]. Other than dimensions, the method captures the color of the object and then uses the collected data in special software for photogrammetry [11]. The advantages of this method are low cost, high precision, speed, and the ability to be applied to large-scale objects [8, 11]. The precision can be proved by the resolution of a few micrometers resulting from the development of algorithms used in the software [9].

On the other hand, one of the disadvantages of the method is that the data needs to be large enough for the reconstruction of the object [12]. Also, the cost of the equipment is high, reaching up to \$50,000 [12]. Previously mentioned large amounts of data should consist of high-resolution images to output accurate results which causes a long time for algorithms to process the data [11]. The applications of photogrammetry include areas such as city modelling, medicine, zoology, forest analysis, archaeology, anthropology, survey of areas, and topography [9, 13]. Another specific usage of this method is the reconstruction of the bones of the Edmontosaurus which is done by the reflex camera and Zeiss lens [14].

2.1.2 CT scanning

Computerized Tomography or CT scan is the method of scanning used in medicine to acquire images of the inner part of the human body through the use of X-rays. The equipment utilizes the X-ray to scan 2D slices of the volume of the body [8]. The collection of the images is then used in the process of 3D reconstruction, which includes steps such as transformation, perspective creation, clipping, lighting, rastering, shading, texturing and anti-aliasing [11]. The 2D images resulting from the scan are usually saved as raw or DICOM (Digital Imaging and Communications in Medicine) formats, which are then imported into a special program for rendering [10]. The main advantage of this method is the ability to observe the internal parts of the objects [11]. That is important for the investigation of the hidden structures which can remain unnoticed in other scanning methods [9].

However, the high cost and long duration of the scanning procedure are disadvantages of the method [12]. In addition to the high cost, the equipment for this type of scanning is usually found only in medical facilities [9]. Also, the quality of the results can be low due to the error in the combination of the 2D images, which is caused by the wrong positioning of the object [15]. Similarly to the previous error, defects, or in other words artifacts, are possible during the scanning, such as partial volume effect, beam-hardening, frozen-noise, and partial volume averaging [10]. Other than medicine, the method can be applied in archaeological procedures due to the non-invasiveness of the CT scan [10]. Additionally, the Toshiba multidetector CT was used in the UCLH (University College London Hospitals) to scan the materials with accuracy at the millimeter level [15].

2.1.3 Surface laser scanning

One of the popular methods of 3D scanning is laser scanning which uses a laser pointed at the surface of the object and then deformation is measured [8]. The working principle of the laser scan can be explained by the trigonometric triangulation method: the laser emitted by the scanner is reflected by the object and the reflection is then captured by the stationary sensors [8]. The laser scan is better than other methods due to high resolution and high accuracy which makes the scanning of small-scale items possible [11]. The accuracy of the method is enough for the scanning of the museum exhibits [11].

In contrast, the abundance of the possible outcomes of the scan due to variable points of view makes the post-processing part longer than scanning itself up to 5 times [10]. Another limitation is the instability during the scanning of transparent and shiny objects [11]. The equipment which utilizes this method can be in stationary, portable, CMM-based (Coordinate Measuring Machine), and other forms [8]. For instance, the Next Engine stationary scanner was used in the scanning process of the cane toad [16]. Also, the method can be applied in archeological studies [11].

2.1.4 Structured light scanning

Another method of 3D scanning is structured light scanning, which is also a surface scan similar to laser scanning, but uses the projection of structured light on the object to measure the deformation in the grid and obtain the shape of the object [8]. This scanning method works by the use of triangulation and white light. The projected light forms the patterns on the surface of the objects, which deform due to the shape. These deformations are then used for the calculation of dimensions, which in turn are used for the construction of the model [11]. One of the reasons to choose this method over others is the precision reaching 30 micrometers in the scanning of the skeleton surface [17]. The precision allows the resolution of the result to be up to micrometric values [14]. Other than resolution, the high speed of scanning and the possibility of scanning large-scale objects are advantages of the method [11]. Similar to laser scanners, structured light scanners have scenarios where defects can appear, one of them being artifacts due to the scanning of the wet object [17].

In addition, the scanning process takes longer than the photogrammetric method of scanning [14]. The last problems are the need for frequent calibration of the scanner and the high cost of the equipment [12]. The structured light scanner was mentioned in the research papers that studied the digitization of the bones. One of them used the Aztec Space Spider to scan bone parts in wet and dry conditions [17]. Another one used SLS-2 to replicate the dogfish chondrocranium [16]. Also, EinScan Pro was used in the replication process of fossil skeleton bones with an accuracy of up to 0.045 millimeters [18]. Other than professional 3D scanners, the Kinect, which is based on the same method as other 3D scanners, was used in paleontological research to reconstruct the object [12, 19].

2.1.5 The contact scanning

The last type of 3D scanner that will be mentioned is the contact 3D scanner, which uses the probe movement over the surface of the object to obtain the shape and dimensions [8]. The working principle of the contact scanner can be explained on the basis of the MicroScribe digitizer. The MicroScribe, which has a stylus tip, moves over the surface and creates landmark points [9].

Another example is the CMM, which can have several probes that capture the coordinates of the points relative to the reference and create the point cloud which will be used in the construction of the simple mesh nodes [20]. The advantages of the contact scan are a low standard deviation of 0.1 millimeters and an accuracy of up to micrometers [9, 24]. The disadvantages of the method are significant compared to the drawbacks of other methods, including the possibility of altering the surface due to physical contact of the probe with the surface [11]. Also, previously mentioned CMMs have high costs and require regular maintenance [20]. Furthermore, the linear process of taking the measurements may lead to errors such as incorrect data points or the absence of some of them [9]. The application of such methods includes industry, manufacturing, and quality control [11, 24].

2.2 Additive Manufacturing Process

2.2.1 3D Printing Methods

3D printing or Additive Manufacturing (AM) is a rapidly developing technology used to design complex models with the highest accuracy and minimum waste. Unlike conventional machining, AM has no limits on the model's geometry. Consequently, it is a suitable method of replicating bones with different shapes, structures, and roughness.

There are various methods of 3D printing, such as Stereolithography (SL/SLA), Fused Deposition Modelling (FDM), Powder Bed Fusion (PBF), Selective Laser Sintering (SLS), and so on. Since SLA and FDM are available at the university, it was decided to consider these techniques first and choose the optimal one.

Figure 2.1 shows the working principle of STL. First, a platform is covered with a layer of photosensitive polymer. Then, it is crystallized after exposure to a laser beam. This process continues until the desirable geometry is achieved [21].

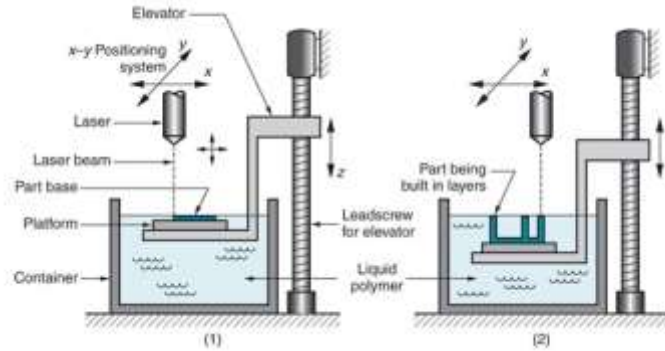


Figure 2.1: Process of 3D printing with Stereolithography [22].

Unlike STL, the laser beam is not involved in FDM. The filament (wax or polymer) quickly solidifies after being extruded from the nozzle [22]. As can be seen from the figure below, the part is manufactured layer-by-layer:

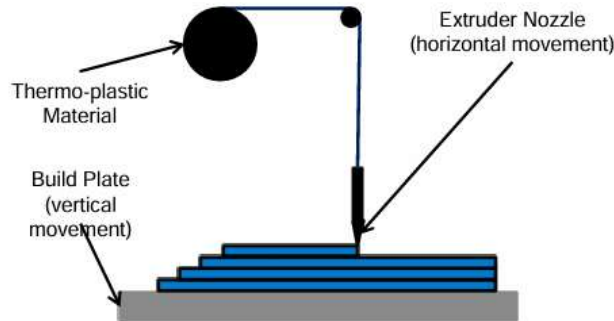


Figure 2.2: Process of 3D printing with Fused Deposition Modeling [22].

SLA printing utilizes resin polymers, which results in the models being durable to temperatures but brittle [21,23]. Another advantage is the ability to use different resins while printing an object, which is called multiple material stereolithography [24]. The method produces with high accuracy, allowing them to be detailed in their parts and the surface finish; however, the method does not work well for details with overhang [21]. Additionally, the method is rather slow, and the material is expensive [23].

FDM utilizes either ABS - Acrylonitrile Butadiene Styrene - or PLA - Polylactic acid. ABS has a lower price and produces models that are lightweight and impact, heat, chemical, and abrasion resistant [25, 26]. However, the models are also prone to warping and changing color due to oxidation of the polymers of the ABS [25, 26]. PLA is biodegradable and biocompatible [25]. It has a low melting point, leading to a simpler printing process with no toxicity or irritation caused to the environment and workers [26]. However, at the same time, the models produced are brittle and have weak mechanical properties [25]. The list of pros and cons of each method can be found in Table 1.

Table 2.1: Advantages and disadvantages of STL and FDM [21].

Process	Advantages	Disadvantages
Stereolithography	<ul style="list-style-type: none"> - High-quality surface finish - Suitable for complex geometry - Great accuracy - High thermal stability - Applications include patterns for casting 	<ul style="list-style-type: none"> - Relatively slow - Expensive - Not suitable for overhanging models - The material is difficult to handle
Fused Deposition Modelling	<ul style="list-style-type: none"> - Great surface finish - Cost-efficient - Optimal for compound shapes - Flexible - Absence of scrap 	<ul style="list-style-type: none"> - Slow process - Average quality

2.2.2 Filaments

Each additive manufacturing technique and 3D printers have a specific list of supported materials. PLA is one of the most commonly used filaments in 3D printing. It can be obtained by two methods: polymerization of lactic acid and lactide's ring-opening polymerization [27]. As was mentioned earlier, the main advantages of PLA are cheap price, simple printing, and biodegradability [25]. Initially, the application of PLA was limited by implantable devices and tissue scaffolds due to the low molecular weight and expensive price [27]. With the advancements

of technology, the molecular weight of this material was significantly reduced and it became more affordable, which enhanced its utilization. PLA experiences glass transition at around 60°C where the material softens and starts deforming [28]. There were multiple cases reporting the melting of PLA printed parts melting under sunlight that went and warped through glass so the matter of storage needs to be well thought and planned for this type of filament.

Moving on to the next type of polymer, three different monomers called acrylonitrile, butadiene and styrene form the ABS. This type of polymer shows high thermal resistance, flexibility, and lightweight [29]. The conventional fabrication method of the ABS is chromic acid bath; however, sustainable processes like surface etching and activation techniques are being developed to reduce the environmental impact of the production [29]. Moreover, improved fabrication increases the adhesion strength of the material.

To talk about materials used for stereolithography, liquid monomers or photopolymer resin is used to create cross-linked polymer structures [21]. These structures form the solidified layers after being exposed to UV rays. The resins consist of epoxy or monomers, photoinitiators, and UV absorbers [30]. The resins have high precision, good surface finish, and accuracy, nevertheless, their main disadvantage is the tendency to shrink once the curing happens [30]. This material also has cons such as longer curing time and sensitivity to oxygen and moisture during curing that can inhibit it even more [31].

2.2.3 Printers

Four types of printers were available at the university: Bambu Lab X1 Carbon, Bambu Lab X1E, Ultimaker 2 Extended Plus, and FORM 4 SLA printer.

Bambu Lab X1 series 3D printers use the FDM technique, have a LiDAR resolution of 7 μm , dual auto bed leveling, and a build in value of 256 x 256 x 256 mm (see Fig. 2.3-2.4) [32]. The maximum nominal speed (500 mm/s), filament type and diameter (1.75 mm), sensors, and physical dimensions are the same for both printers. However, X1E has additional features like active chamber heating, air purification, and most importantly, network control. The enhanced connection options provide robust network communication, off-cloud operations, AI failure detection, and automated filament management [32].



Figure 2.3: Bambu Lab X1 Carbon printer [32].



Figure 2.4: Bambu Lab X1E printer [32].

The Ultimaker 2 Extended Plus printer uses the same FDM technique, but the maximum speed of this printer (300 mm/s) is significantly less than the Bambu printers [33]. However, the range of the supported filaments is extremely high and reaches up to 300 materials, and the filament diameter is 2.75 mm. This printer does not have network control. The picture of Ultimaker 2 Extended Plus was provided in Fig. 2.5.

Lastly, FORM 4, manufactured by Formlabs, uses the SLA technique (see Fig. 2.6). It has the slowest nominal speed of 100 mm/hour and the smallest physical dimensions, compared to other printers [34]. Since the working principle of SLA is totally different from FDM, the supported materials are not plastics, but various types of resins such as alumina resin, elastic resin, etc. It has a network control system including Wi-Fi, Ethernet, and USB 2.0 [34]. Also, it is the most expensive printer among the four and costs around 6 000 \$.



Figure 2.5: Ultimaker 2 Extended Plus printer [33].



Figure 2.6: FORM 4 SLA printer [34].

The complete table comparing the technical characteristics, manufacturing methods, and costs of the printers is provided below:

Table 2.2: Comparison of 3D printers.

Parameter	Bambu Lab X1C [32]	Bambu Lab X1E [32]	Ultimaker 2 Extended + [33]	FORM 4
Build Volume	256 x 256 x 256 mm		305 x 223 x 223 mm	200 x 125 x 210 mm
Nominal Maximum Speed	500 mm/s		300 mm/s	100 mm/hour
Technology	FDM			SLA
Supported material	PLA, PETG, TPU, PVA, BVOH; ABS, ASA, PC, PA, PET; Carbon/Glass Fiber Reinforced PLA, PETG, PA, PET, PC, ABS, ASA; PPA-CF/GF, PPS, PPS-CF/GF		More than 300 filaments, including PET CF, PLA, PETG, ABS, CPE, CPE+, Nylon, PC, PP	Tough 1500 resin, precision model resin, flame retardant resin, alumina resin, elastic resin, castable wax resin
Filament diameter	1.75 mm		2.85 mm	-
Network control	No	Yes	No	Yes
Cost	1 499 \$	3 000\$	2 999\$	6 000\$

2.3 Bone assembly techniques

2.3.1 Conventional assembly methods

The conventional assembly of the bones usually consists of metal rods and wires that connect the bones. The full skeleton can be mounted on the ground or hung on the wall or ceiling. First, the desired pose of the dinosaur is selected. Then the metal framework holding the skeleton, called the armature, is fabricated. The material is bent according to the shape of individual bones; after that, the cushions are added to provide stability and security of the bones [35]. The example of the dinosaur skeleton assembled by using traditional methods can be shown in Fig. 2.7. The structure of the mount may depend on the material of the skeleton. If the original bones are displayed, then the bones are not drilled and each of them should be easily assembled or disassembled to be examined later [35]. In contrast, the replica made by casting or 3D printing can be machined and grouped into sections.



Figure 2.7: Mounted dinosaur skeleton [35].

The National Museum of Kazakhstan created assemblies of multiple diverse prehistoric animals using conventional bone assembly techniques. The support rods are hidden within the leg bones for aesthetic purposes while most of the bones are connected either through using metal

framework or screws. Some of the larger components, for example the dinosaur's skull in Fig. 2.9 are hang on the ceiling with wires for stability.



Figure 2.8: Brachiosaurus assembly in National Museum of Kazakhstan.



Figure 2.9: Tyrannosaurus rex assembly in National Museum of Kazakhstan.

The Natural History Museum of London on the other hand, have completed an assembly project that wholly depended on the armature and the small support structures made from wires that are attached to it (see Fig. 2.10).



Figure 2.10: Stegosaurus assembly process in London's Natural History Museum [36].

2.3.2 Non-conventional assembly methods

One of the non-conventional assembly methods researched as a potential technique to utilise is using joints to connect the bones. This method makes it possible to move the connected bones in a way similar to how the living creature would have moved. A similar project of reconstructing a dinosaur skeleton using additive manufacturing called InnoDino used the said joints method, investigating the feasibility of various joint designs in their specific structure. The used joints had a purpose of sustaining tensile force as well as holding dinosaur limbs together with high friction when connecting the dinosaur's spinal bones, arms and legs [37]. The assembly in that case was manual, the authors created holes in the bones during the printing process and then put the pegs inside, fixing it with a strong epoxy mixture.

There is also a different approach to creating joints using non-assembly mechanisms that makes the process more efficient and less time-consuming. It could also withstand heavier loads compared to the manually assembled joints discussed earlier. Although very attractive, this method requires various AM processes such as material jetting, metallic powder bed fusion and advanced FDM which were not available for this project [38]. Both of these methods were found to be difficult to implement because an ichthyosaur's long body would need to be supported in a way that continuous articulation would only complicate.

3. Methodology

3.1 Bones

This project works with 138 unique bones of the full ichthyosaur's skeleton identified by the School of Mining and Geosciences experts. They do not make up the full skeleton and there are additional bones that were found during the expedition. However, the additional bones are either in a bad condition or do not have the surrounding bone segments that make it impossible to identify their position and function. The available bones are divided into several parts.

The first part under consideration is the vertebral column which consists of 46 bones. 29 of them are of good quality, making this section one of the best preserved ones of the skeleton. Other bones are damaged due to external factors. Most of them contain breaks and cracks or were

damaged due to taphonomic distortion of fossils. This is caused by the fact that the bones lay in the same position for a long time.



Figure 3.1: Spine bones.

On top of the vertebral column there are Y-shaped neural arches. Most of the bones that were found were in a shattered state. There is only one available assembled bone - it was glued together from available parts so the bone has visible cracks. It is not known why only one bone was reconstructed, however, as it is expected that all of the bones have the same shape, it is enough for this model - all of the other bones that make up the neural arches will be duplicated from the available bone and scaled accordingly to the size of the vertebrae bone.



Figure 3.2: Y-shaped neural arches.

The next part is the ribs of the skeleton. The ribs found during the expedition were in a bad condition because they were shattered into hundreds of pieces. There are only two available rib bones already assembled from the parts. The number is explained by the fact that due to the size of the pieces it is hard to identify their relative position. They are glued together so there are a lot of cracks and empty spaces on the bones themselves. As there are no more available ribs, these two will be used for duplication to recreate the entire rib cage. Here, the existing skeletons were used as a reference to understand the number of ribs necessary and how they should be scaled along the body.



Figure 3.3: Rib bones.

The back part of the skeleton consists of tail bones and back paddle bones. Most of the tail bones are absent and only five of the bones were available. Out of them, two are located near to the end of the vertebral column. The other three should be located at the end of the tail and have a diameter of 20 to 50 millimeters. This creates a sudden transition between the vertebrae and the tail. For the bones that created the back limb, a couple of them were broken, however, there were symmetrical bones that were intact. The available whole bones were mirrored to replace the broken ones. As for the paddle itself, it is found that many of the phalanges that were supposed to make up the paddle are absent. They were reconstructed using a reference from the existing skeletons out of the bones that are of unknown position - they could be equally well from the front and the back paddle.

The parts of the front limbs - shoulder joints, scapula, and humerus - are intact and in good condition. The front paddles are made up of different phalanges. They are also reconstructed with a reference to existing skeletons.



Figure 3.4: Front paddle phalanges.



Figure 3.5: Back paddle phalanges.

The skull of the ichthyosaur cannot be reconstructed at the moment. A lot of its parts are missing or cannot be identified. There are around 20 to 30 bones that were found but cannot be located relative to the identified bones due to the fact that the surrounding bone segments are absent. There is only one available identified part which is half of a lower jaw. The second half is missing so the available part is mirrored for the reconstruction. There is also a part of the skull that is identified to be the forehead part, however the surrounding parts are missing.



Figure 3.6: Bones of the skull.

3.2 Scanning method

The scanning method was chosen to be surface laser scanning due to its satisfactory accuracy and availability at Nazarbayev University. Other methods mentioned in the literature review are either unavailable - CT scans are mostly stationed in hospitals - or require a lot of devices that would make the process more resource-consuming but also result in worse quality, like photogrammetry that requires cameras in all three degrees of freedom. The chosen method also has the advantage of having a designated software that allows for manipulations with the digital model: removal of damages, and change of the applied parameters.

The scanner chosen for the digitization of the bones is ZEISS T-SCAN. It functions through the emission of a laser beam onto the surface of the target object. The device consists of the following components:

- ZEISS T-SCAN hand-held line scanner: a part of the optical measuring system. It has two main sensors. The first one emits an optically expanded laser beam in the shape of a horizontal line. The second one is a 2D camera that detects the laser beams that are reflected from the target object at a particular angle. It also has a pillar beam that is used as an aid for the user to place the scanner in the correct position to scan. The scanner is recommended to be placed perpendicular to the scanned object at a distance of 150 mm. The scanner has

28 markers around its housing that are used to stabilize the scanned image and to minimize artefacts and defects of the object [39].



Figure 3.7: ZEISS T-SCAN hand-held line scanner.

- ZEISS T-TRACK 10: optical tracking unit that has 3 built-in cameras. The cameras detect the position of the hand-held scanner by recognizing the position of its markers. The desired working distance between the target object and the T-TRACK 10 is 2-4.5 meters [39].



Figure 3.8: ZEISS T-TRACK 10 camera.

- ZEISS Controller T-CONTROL: provides power to the T-TRACK and the T-SCAN and collects and bundles collected data to transfer it to the connected computer.



Figure 3.9: ZEISS T-CONTROL Controller.

The data received from the T-CONTROL is computed through Colin3D software. Before the object is scanned, one should choose the correct scanning parameters such as:

- **Measurement mode.** The measurement mode for this work is “Surface” as the object is static and the software is able to visualize the surface without considering the possible movement. To scan the surfaces in another plane, one must first turn on the “Relocation” function and scan the previous plane again before scanning new surfaces to let the software know the relative position of the two surfaces. This leads to the process becoming more time-consuming as the surfaces have to be rescanned for the 3D object to be formed correctly in the software.
- **Exposure time.** This work uses the 0.125 ms setting which is optimal for this measurement mode [40].
- **Maximum allowed error.** As the model does not require great surface detailisation, this setting is set to 50 micrometers which allows for a quicker scanning process [40].
- **Maximum angle of incidence.** This setting is at 30 to increase the quality of the data [40].
- **Fill gaps.** This setting is at its maximum at 16 millimeters as the bones have a lot of microfractures that could be removed by the software automatically allowing us to skip this step in the pre-processing [40].
- **Scan line width.** This is set to 40% to minimize the unnecessary scanning of the outside objects such as a surface under the target object.

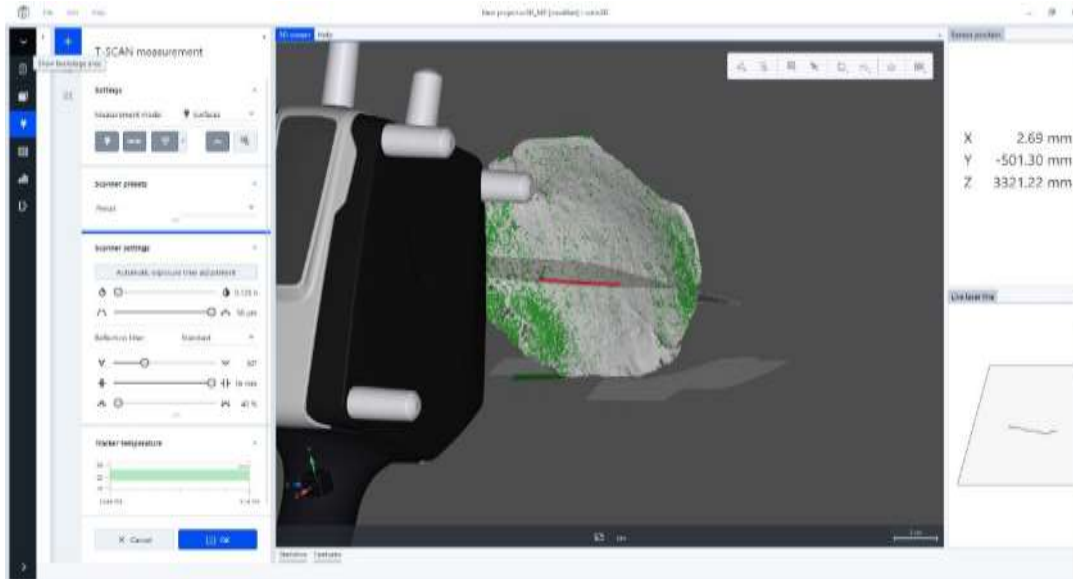


Figure 3.10: Colin3D software.

During the scanning process, the scanned target object is placed in front of the T-TRACK 10 camera at a distance of 2.5 meters. At all times of scanning, there should not be an obstruction between the T-TRACK 10 and the markers on the hand-held T-SCAN [39]. The data from the T-TRACK 10 is transferred to the T-CONTROL and then to the software. The resulting scan has 100,000 - 200,000 mesh nodes, thus requiring post-processing to decrease that number to make the files easier to work with. The chosen mesh creation optimization method is “Design” which allows for an optimization of the number of mesh nodes while also allowing for manipulation of the object such as smoothing and remeshing [40].

3.3 Mesh optimization and Bone restoration

As was previously mentioned, the scans of the bones consist of a large number of mesh nodes that need to be decreased in order to optimize the printing and analysis processes. The raw data that results from the scanning goes only through one stage of filtration. Additionally, the relocation function, which is used to capture the change of position of the object, creates an overlap of data. As was said in the previous section, it is needed to scan the surfaces that were scanned in the first half of the procedure again in order for the software to understand how exactly the object changed positions. As the surface is scanned twice, the software counts it twice, overlapping the data points. This creates unnecessary mesh nodes in the raw data. To fix this problem, global optimization was

used which optimizes the measurements within one group removing the overlapping data. Figure 3.11 shows how the scan looks in its “raw data” state. Figure 3.12 shows how the global optimization function shows which regions of the scan were overlapping and glued together into one layer after the optimization.

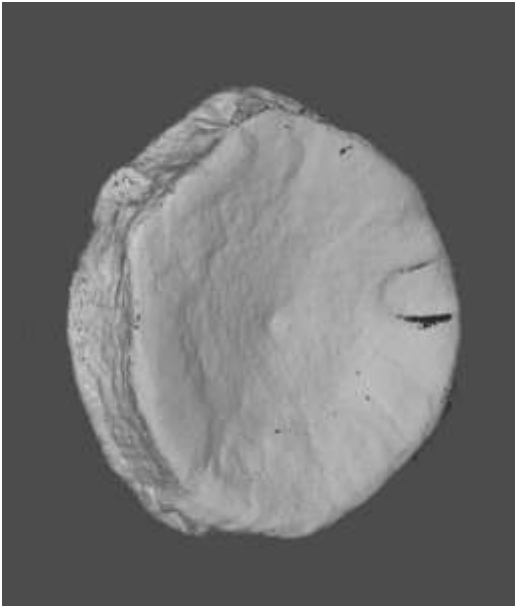


Figure 3.11: Raw scan.

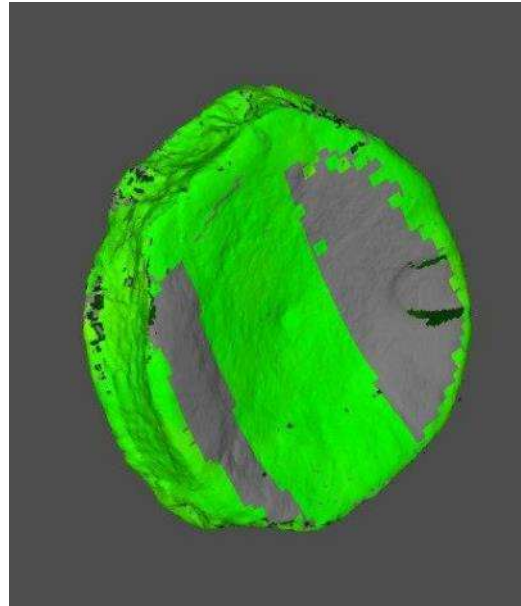


Figure 3.12: Global optimization result

Next is the process of mesh creation to decrease the number of mesh nodes of one model. The software includes four types of mesh creation: quality control, design, reverse engineering, and none. As one of the set goals was to decrease the number of mesh nodes, choosing the “none” mesh creation type was unfavorable. The quality control type does not fit the project goals because after the procedure the mesh count does not decrease to the extent that is needed. Besides, it creates surfaces that are very precise to the scan - as needed for projects where details are an important consideration. However, in this case, the exact details of the bones are not as important. Additionally, this mesh creation method takes a long time to process. The reverse engineering type of mesh creation also does not fit this project’s goals. This type is used when a project requires digital profiles of objects for future research and testing - which is not a part of the goals as of now. The method also does not do smoothing of the objects while also utilizing sharpening and sharp edges are not something that is often encountered while working with fossilized bones. The

design type of mesh creation is the most appropriate type as it does smoothing and also decimates the mesh.

After mesh optimization, some of the models still contained empty spaces and holes. These were fixed using the “edit holes” function that filled the holes with either a planar or a curved surface. To simplify the printing process, the models also went through smoothing of the surfaces and sharpening of the edges to minimize the number of small surface scratches. Besides that, the scanned models often had some outside surfaces such as the table that the bone stood on or the material that was used to fix the bone in one place. Such things were removed using the “lasso selection” function. Such things were highlighted using the tool and deleted in the software.

As was previously mentioned in section 3.1, the scanned bones had some imperfections that needed to be fixed before the printing and analysis. One such problem is cracks and breaks. They were usually rather small in size and only on the surface of the bones. For some of the bones, the imperfections were due to the restoration process. As some of the bones were shattered into several pieces, it was necessary to glue them together resulting in a visible seam between the pieces or glue being visible on the outside surface of the bone. Such imperfections were first removed using the “lasso selection” tool and then the missing parts were filled using the “edit hole” function.



Figure 3.13: Unprocessed bone.

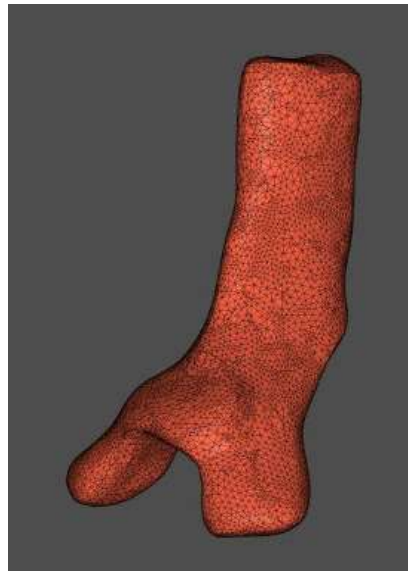


Figure 3.14: Fixed bone.

Some of the bones were heavily damaged even after a design type mesh creation. To remove the artifacts present on those bones several iterations of smoothing were applied. If there was still a significant problem, the missing parts were filled using the “hole edit” function with either a planar or curve mode. The state of the bones before and after such processing can be seen in figures 3.13 and 3.14.

Many of the bones were either the only ones of the group or had an intended symmetric bone that was heavily broken or absent. There were attempts to scan as many bones as possible to preserve the natural state in which the fossils were preserved. However, in many of the cases it was impossible to utilize the fossils themselves for the model: some bones were too broken or missing large pieces; some bones were difficult to fix; some symmetric bones were absent. In these cases, reflection of elements was utilised or in other words mirroring of the scanned bones that was available. This method was also used for the cases where the bones were identical to one another and it was optimal and permissible to utilize reflection of elements. One such example is the aforementioned jaw of the ichthyosaur. There, the second half of the jaw was either missing or heavily broken. Since it is assumed that the two halves of a jaw would be symmetrical, it was decided to utilize the scan of one half to mirror it for the second half of the jaw.

The ichthyosaur skeleton also has some repeating parts such as ribs, y-bones of the neural arches, and the tail. These parts were also the ones for which there was a small number of assembled and identified bones instead of the whole range. To create a model that contains all of the bones, the duplication of elements method was utilized that gives opportunity to use one model and duplicate and scale it along the vertebral column.

Additionally, the extrapolation method was used when referencing the existing specimen created by other paleontologists to understand how all of the available bones should be assembled together. This was used on the parts of the previous paragraph to understand how they should change along the body. It was also used for the recreation of the paddles that consisted of a large number of bones and phalanges arranged in a particular pattern. Without a previously existing specimen example, it would not be possible to deduce how the phalanges should be arranged to form the front and the back paddles.

3.4 Printing method

The chosen printing method is FDM. SLA requires expensive resources which are unavailable for this project. For the printing of the first bone, the Bambu Lab X1E Combo FDM 3D printer was used (see Fig 3.15). It has a high resolution of 7 μm and an acceleration of 20000 mm/s^2 [32]. There are different available filaments such as PLA, ABS, PET, and TPU, and for the first bone, black ABS was used.



Figure 3.15: Bambu Lab X1E Combo 3D printer [32].

The printer has a special slicing software called Bambu Studio, which applies to all Bambu Lab printers. Here, parameters like speed, support, strength, and quality can be regulated. The display of the Bambu studio is provided in Fig 3.16.

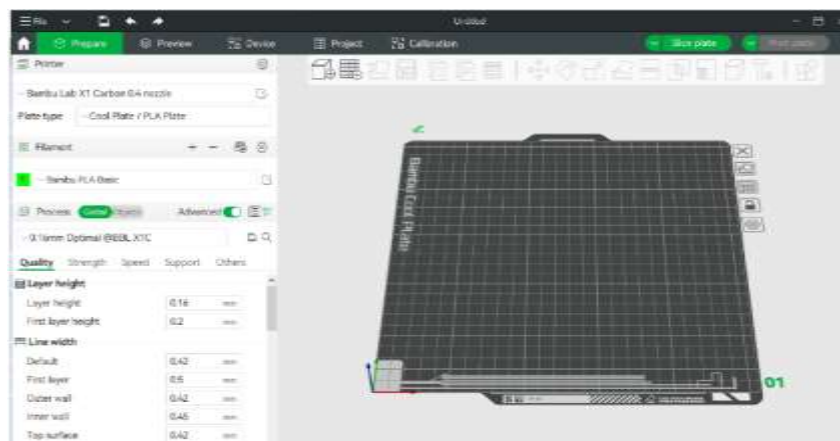


Figure 3.16: Display of the Bambu Studio.

The Bambu Lab X1E printer was continued to use for all of the details. Overall, depending on availability, parts were printed on one to three printers at a time. For the filament it was decided to use PLA+ type in color bone white so that the printed bones would be aesthetically pleasing and close to real well-preserved bones.

Most of the print settings that were used were standard ones. The print height was 0.28 millimeters. Previously 0.1 millimeters height was used for higher accuracy, however, it was discovered that printing in thinner layers will result in a longer print time. This way, one particular bone would take 58 minutes to print with a height of 0.28 millimeters. This same bone will take 1 hour 48 minutes to print with the height set to 0.1 millimeters. As can be seen, there is almost a two times difference between the printing time, which is significant considering the number of bones that was needed to print. The printing speed was set to 50 millimeters per second. The sparse infill density was set to 15%. It was considered that the bones will not have to deal with a large amount of force acting on them, so the 15% infill density was permissible. The gyroid infill pattern was chosen due to the fact that it would create a structure that would have good support from all angles. In assembling the skeleton, a connection could be placed at any place of the structure, so a gyroid pattern would be a safe choice. The support of the internal structure was preferred over the fact that this pattern will result in a higher use of material and longer printing time.

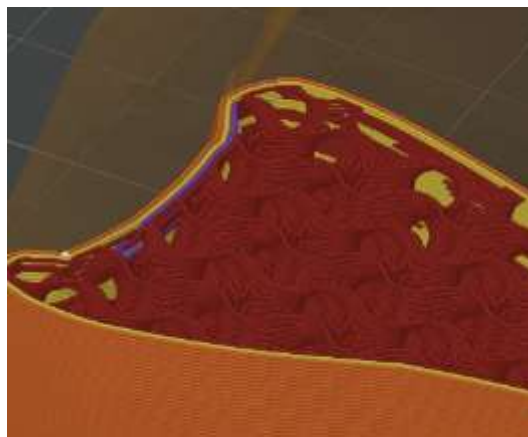


Figure 3.17: Gyroid filling pattern.

The chosen support type was tree. It is a support type that would take less time to print. Another consideration is that this model does not have to have very accurate details, so the tree support type is a good choice over other support types that would preserve the details better. Lastly, the rafts during printing were considered. Raft is a layer of material under the object separating it

from the printing plate. If the bone that was printed had a geometrically complex side in contact with the printing plate, attempts to minimize that contact to prevent deformation by using rafts were made. If the printed object had a flat side contacting the printing plate, then there was no raft.

3.5 Assembly

The assembly of the ichthyosaur is firstly done in the Solidworks. For that the measurements of the scanner are needed to be converted into PLY or STL files first for further usage. After that, the skeleton bone parts files are uploaded into the software and converted into the Solidworks part file. During the process the mesh size of the parts is reduced such that the whole assembly will not require huge amounts of computational power. The important point to mention here is that the parts with reduced mesh size and decreased accuracy are only used for the digital assembly, whereas the physical printed parts are done with the original measurements parts. After converting the parts, they are assembled in the order similar to the real life appearance of the ichthyosaur. The process was done using the provided table with the numeration of each bone, their type and description which helped to create layout. The further modifications and readjustments were done with the help of the paleontologist expert from SMG.



Figure 3.18: The digital assembly of the ichthyosaur skeleton.

The assembly of the physical copy of the ichthyosaur starts after the printing process of the bones in the skeleton of the ichthyosaur is completed and the digital copy is assembled. The base support system of the ichthyosaur skeleton was chosen to be the metal frame used as the stand for the poster. The reason is the availability of the rigid, light structure in the campus in the first place. This choice excludes the machining of wood or metal to create the frame for skeleton from scratch. Therefore time and money are saved.

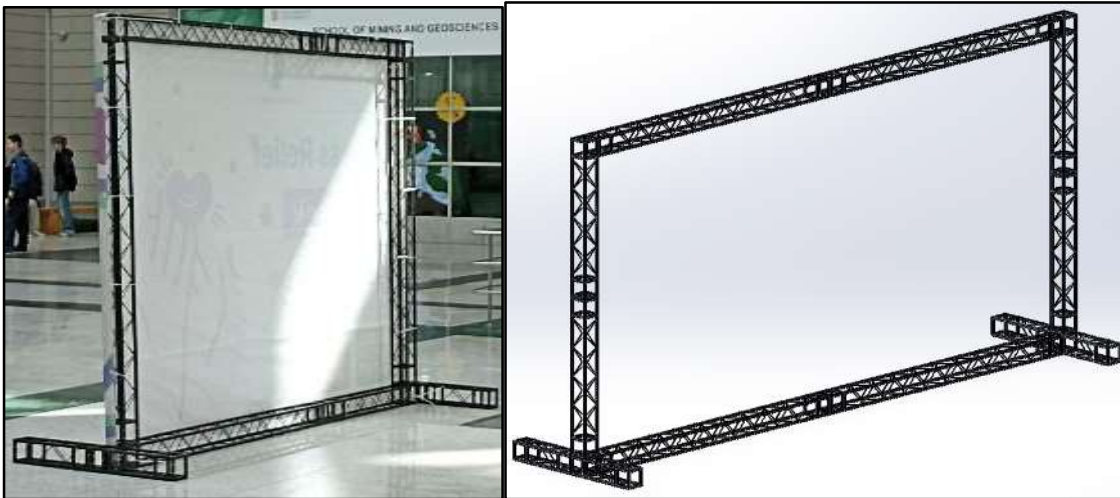


Figure 3.19-3.20: The photo of the frame and the metal frame model.

Next, holes on the spine bones were drilled to let through steel cable with nylon coating which has enough strength and flexibility to withstand the weight of the whole spine which is about 5 kilograms. Previously, the holes for this purpose were designed during the 3D printing stage, but they were too small, therefore drilling was required to widen the holes. Two of the holes were located at one level on the bones, while the third hole was drilled at the center. Pair of holes were used in stabilization of the spine such that the spine will not roll. The last hole fixed their position and ensured perpendicular alignment with respect to cables. After the spine bones were placed on the cables, the both ends of steel cables were tied to the middle points of sides of the frame. The additional fixation was achieved by using construction lines on the cables at a distance of 5 backbones from each other resulting in 10 additional points of support. Another usage of this additional support is to adjust the level of the spine differently on its length. According to the paleontologist's advice the middle part of the spine was positioned higher than other parts of the spine.

Following step is connecting the fins on top of spine bones. The position of the fins were aligned by the upper surface of backbones which have grooves for them. They were fixed by drilling the holes on both connecting surfaces and placing the metal wire inside the holes. Only part of the fins was placed due to time constraints. Another bones to connect to the spine are ribs which connect to the sides of each backbone and are connected in similar manner as fins.

Other bones to assemble are distal fins at the front which is frontpaddle and the end of the skeleton which is the hindpaddle. They were grouped separately. The front sub assembly consisted of fins themselves and shoulder bones. They were connected as described previously and were hung under the first front spine bone and closer to the head bones by construction lines. The back sub assembly consisted of fins and pelvic bones which were fixed the same way and hung under the last spine bone. At the end the head bones were fixed along the nylon steel cables in front of the first spine bone. During most stages of assembling, the plastic clamps were used.

4. Results

4.1 Scanned model

The scanned models were created using the ZEISS T-SCAN. After calibration of the scanner, the standard deviation was found to be 0.034 millimeters. Overall, 138 scans of bones were created. All of the available bones were scanned, however, as per an unofficial agreement, if more bones are made available by the SMG paleontologist in a near future, they will also be scanned for the sake of preservation of data. All of the scans are kept on the laptop connected to the T-SCAN at the laboratory for possible future use and on a personal computer of the team members for the sake of the work on this project - change of the scan file and printing.

At the beginning of this project work, a scan of one bone took from 40 to 60 minutes. That was considered to be too long considering the number of bones that were needed to be processed. The scanning process was made faster after a change of settings. With the new version, in the same time of scanning, larger surface area could be scanned at the expense of the quality of the scan. The change in the quality was permissible as smoothing would still be applied to the models that will get rid of the smaller details anyway. A scan of one bone now took 20 to 40 minutes. The time taken for the scan differed depending on the shape of the bone and the quality of its surface. The simpler and smaller bones took only about 15 minutes, while larger bones or bones with a particular shape took up to 40 minutes.

After a scan is processed through the software, it is preserved in a SC3D_MP format. This format preserved raw data as well as the data after post-processing changes. These files are large totalling 140 gigabytes. After filtration of the data and a change of the format to STL the files weighed only 100 megabytes. That can be explained by the fact that the new format contained only information on the surface mesh nodes of the final version of the model.

4.2 Structural analysis

The original scan was saved in sc3D_MP format and could not be exported as a CAD file, so the conversion of the graphics into a 3D model was required. The bones were saved in IGS and STL formats with 2 different resolutions of 20,000 mesh nodes and 100,000 mesh nodes. At first, the

ANSYS Workbench was seen as a suitable software due to its simplicity in performing static structural simulations. However, it could not open any file with a higher resolution and generate a mesh on the ones with a lower resolution. Therefore, it was decided to switch to SolidWorks 2024. To convert the scanned graphics file into a CAD model, the *Scan to 3D tool* and the *Mesh Prep wizard* function were used. This tool converted the STL file with 20,000 mesh nodes into a solid body. The 3D model with the initial number of mesh nodes can be seen below:

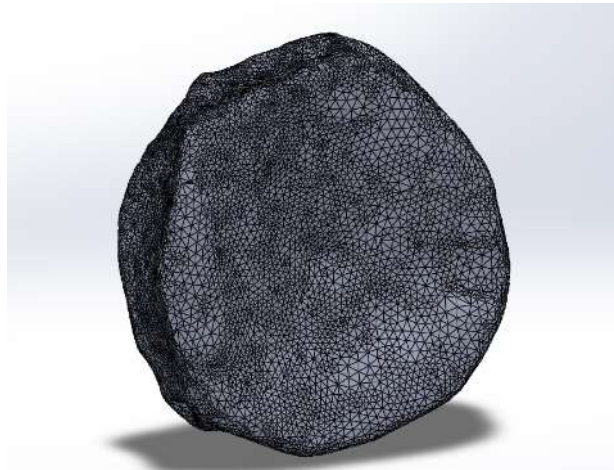


Figure 4.2: Bone with initial 20,000 mesh nodes.

Then, characteristics like volume, surface area, and center of mass were found from the mass properties of the part (see Figs 4.3 and 4.4).

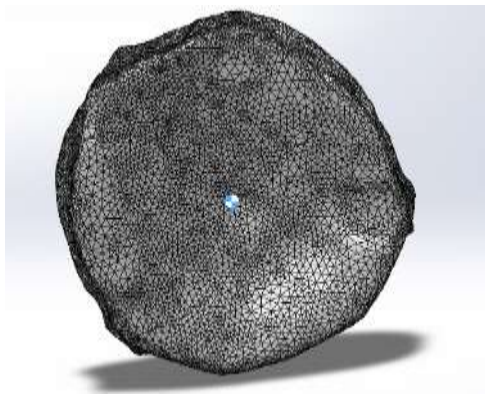


Figure 4.3: Center of mass.

```
Volume = 220126.59052 cubic millimeters
Surface area = 32969.72169 square millimeters
Center of mass: ( millimeters )
X = 215.20244
Y = -626.33391
Z = 3067.96450
```

Figure 4.4: Volume, surface area, and coordinates of CoM.

To test different modification parameters, the number of mesh nodes was reduced by 95%, the error was equal to 1 mm. The final model with mesh nodes can be seen below:

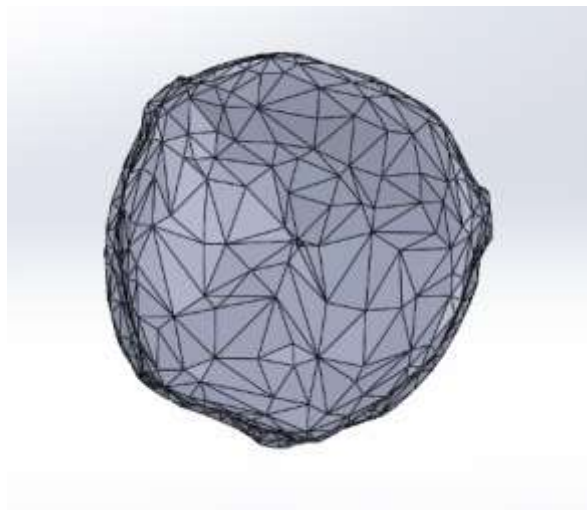


Figure 4.5: 178 Bone with mesh reduction.

The mass of the bone was 80 grams and the custom plastic with the parameters of PLA was set as a material. The bone was fixed at the hole in the middle and two forces of 1N were applied at the cavities on the sides. Since the ribs that were attached to the vertebrae via these cavities have light weight (80-90 grams), the applied force was also small. The part encounters almost zero stress everywhere due to the low force (see fig.4.5).

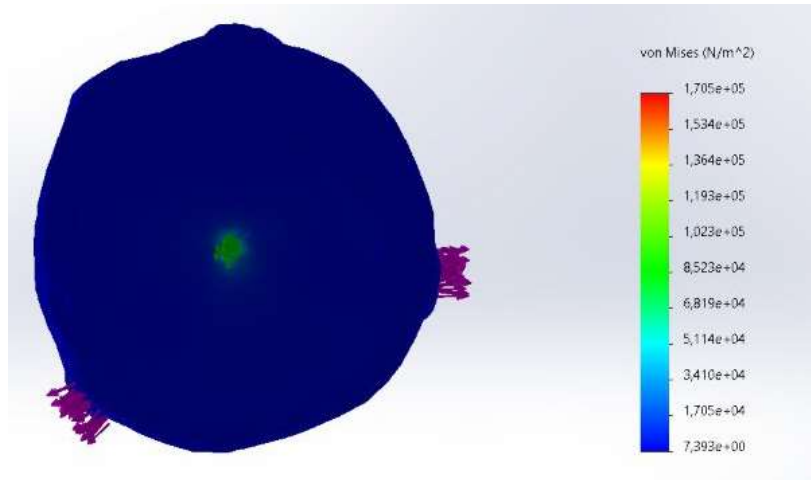


Figure 4.6: Von Mises Stress

In contrast, the highest displacement of 1.408 mm can be seen at the top and bottom parts of the bone, which is decreased towards the center.

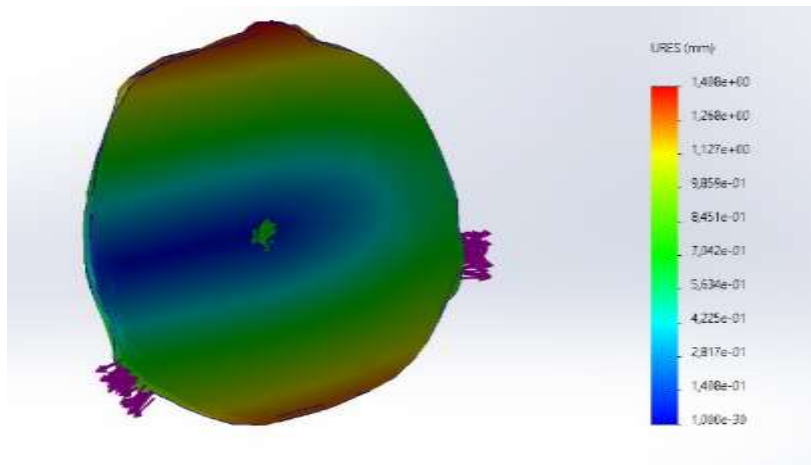


Figure 4.7: Displacement

4.3 Printed model

Figure 4.6 below shows the assembled skeleton of the ichthyosaur as a result of the work done. As of now, the skeleton consists of 190 bones: 48 vertebrae bones, 20 Y-shaped bones, 6 pairs of ribs, 2 large lower jaw bones, 10 bones that constitute the limbs, around a hundred of smaller bones that make up the paddles. The bones were assembled into the skeleton under the guidance of an SMG paleontologist and with reference to the existing models. The estimated mass of the model is around 10 kilograms. The total printing time was around 300 hours. The estimated total length of

the skeleton will be around 3.7 meters, however, that is with the current distance between each vertebrae set to approximately 20 millimeters. .



Figure 4.8: Assembled model.

In the time before the presentation of this project, the bones that were considered lower priority during the assembly process will continue to be printed. This way, the ribs and the Y-shaped bones, as well as the tail of the ichthyosaur will continue to be printed. As was mentioned earlier, the tail bones are mostly missing. They could be reconstructed digitally and printed for the sake of presenting the full skeleton, however, as they would not present real fossils, they were put on the lower priority. The same can be said about the ribs and the y-shaped bones. There, only one or two of the fossils were assembled and identified by the SMG paleontologist, and it was needed to duplicate the available scans along the vertebral column, scaling the bones to be of appropriate size. The current assembly shows that the bones and the understanding of how they should be added to the skeleton were successfully acquired. As all of the leftover ribs and Y-shaped bones will be a simple repetition of the same process, they were considered to be lower on the priority list, preferring to first finish with the more unique bones of the skeleton.

Once all of the assembly will be finished, it is estimated that the total weight of the model will be around 17 kilograms and it will take around 240 more hours to produce. This estimation of time comes from the fact that each rib takes 5 hours to print and the ribs should be present along all of the vertebrae column. The only thing that is planned to not be reconstructed for this skeleton is the upper part of the skull. As was previously mentioned, the bones of the upper part are unidentifiable as of now as many are either missing or it is impossible to locate their position precisely.



Figure 4.9: Close up of the vertebral column.

5. Discussion

The aim of this work was to create an identical replicant model of the presented Ichthyosaurus bones. The result of the work is a skeleton of an ichthyosaurus with as many parts as it was possible to assemble due to limitations on the fossils. The current model will be further improved in the upcoming two weeks with bones of ribs, tail, and Y-shaped bones.

5.1 Condition of the bones

As was mentioned in previous sections, many of the bones are unavailable for scanning. This comes from several factors: some of the bones are missing; others are broken into pieces and cannot be made whole in time; position of some of the bones cannot be determined. For example, figure 5.1 shows the only available bones of the skull. The other ones are missing. Out of the three depicted bones, only one is located. The other bones are assumed to be placed next to other bones that are currently missing. This leads to the fact that, although the bones are present and can be scanned, they cannot be added to the model in a way that is definitely true to the ichthyosaurs' build.



Figure 5.1: Available bones of the skull.

Figure 5.2 shows the fractured state of the rib bones. Only two ribs have been so far made whole. All of the other rib bones are in a state visible on Figure 5.2.



Figure 5.2.: Fractured bones of the ribs.

The difficulties with the assembly of the bones also slow down the process of this work and problems of a lack of physical bones to be scanned for the model. In these cases, the missing and broken bones were reconstructed digitally before being printed. Other bones are distorted due to outside factors, these too were reconstructed before printing as explained in the methodology section of the report.

The phalanges available for the process are mixed together and it is possible that all of the small bones come from the front paddle of the ichthyosaur. This leads to the fact that it was rather easy to build the front paddle, however, for the back paddle the final result cannot be said to be true to how the anatomy of this ichthyosaur was. All of the assembly was made referencing the existing skeletons of other specimens.



Figure 5.3: Resulting paddles.

5.2 Scanning of Bones by Photogrammetry

Multiple 3D scanning devices were tested at the beginning of the semester to find the optimal scanning method for this project. One of the first options that was considered was proposed by the initiator of this project and it was to scan the bones using an iPhone. 3D scanning using an iPhone involves taking measurements of an object using the device's camera and LiDAR (Light Detection and Ranging) sensor. The scan results obtained using two different apps, Polycam and 3D Scanner, are provided below. Polycam is an app for Android that analyzes a minimum of 20 photos of an object from different angles and creates a scanned file. It was installed on a Samsung Tab S7 tablet. Compared to this, the 3D scanner app is available in the App Store and was downloaded to an iPhone 14. The working principle was similar to Polycam, with the exception that there was an option to take a 360-degree video instead of photos. As can be seen from Figs 5.4 and 5.5, the sensor captured the surface that the bone was standing on too and as a result, merged some of their elements or distorted the whole structure of the object, making the acquired models completely unusable. It was later decided that this method was unsuitable for the project.



Figure 5.4: Scan result from the Polycam app.



Figure 5.5: Scan result from the 3D Scanner app.

5.3 Scanning optimization

The scanning process of each spine bone takes about 15 minutes. However, sometimes, due to particularities of the surface of the bone - when the bone has many fluctuations of its surface - the scanning time increases to up to 30 minutes. That is the case because with an increase in fluctuations, the scan should be performed from more angles to minimize the number of empty spaces - the small areas of the bone that are skipped by the T-SCAN when a higher part of the surface is met. While trying to optimize the time of the scanning process, sometimes, holes appear on the surface of the digital model - as displayed in Fig. 5.6. Such empty spaces are filled in post-processing using curve-based hole filling in the Colin3D. For the quality of the scan, the setting is first set to fill holes that are around 10 mm in diameter. If it so occurs that there are holes that are larger than that, the only thing available as of now is to tell the software to fill them - or in other words, ignore them. This leads to a larger difference between the real-life bone and the model, however, that is the only way of optimization that is available.

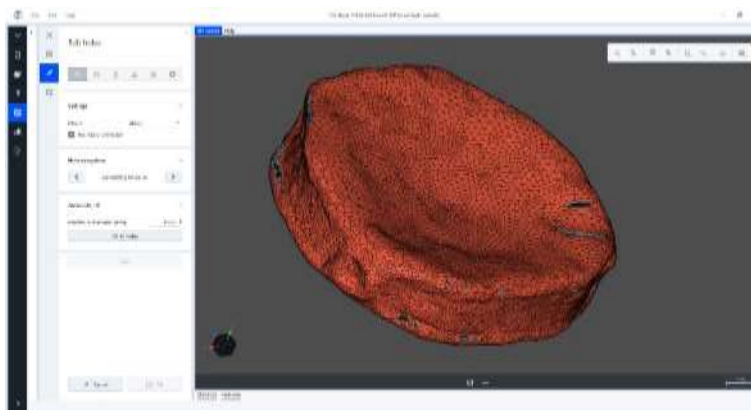


Figure 5.6: Digital model of a bone with holes.

5.4 Software availability

The Colin3D software necessary for the work of the scanner is installed on a laptop of one of the laboratories of Nazarbayev University. The problem was that the available version was incompatible with the CAD-format structures. In order to process all of the available scans, the format of the scans had to be changed to either STL or PLY. Both of these versions did not have the same preservation of data like in CAD. This means that some parts of the scans either did not display well or were simplified. Because of this, additional processing work was required in order for the files to be ready for the printing process.

5.5 Surface quality

One of the problems that is present with the skeleton model is that some of the surfaces have a rather bad quality. That is because in some cases the printing required a close contact between the model and the printing plate. For many of the bones, this problem was solved through either the object being printed at an angle or through the use of a raft. However, in some of the cases - including the phalanges - the rafts were not enough to make the surface ideal due to their small size. The printer would have to work at a higher accuracy, which would also result in more time taken for a print of a single bone. In some other cases, the bones were too large for them to be turned in the printer to an angle where the contact would be minimized. Still, this resulted in some surfaces looking incomplete.

6. Conclusion

Overall, the progress of creating the model of the Ichthyosaurus is successful. Most of the skeleton is already printed and assembled. The leftover available bones will be printed and assembled before the presentation of the capstone project. The team will continue to work on completing and improving the skeleton until the presentation. The current results of the work can be found in the previous section. The skeleton model is turning out to be a good representation of the anatomy of the ichthyosaur and should be a good educational material. Additionally, the methods used in this work could be applied for future projects with a goal of creating a 3D model of fossils.

7. Future Work

The future work that will be done in the near future is the finishing of printing and assembling of the ribs and the Y-shape bones, as well as the tail. If any bones will become available in the near future, they will also be scanned outside of this project in order to preserve a digital version of the bones.

Some of the possible research that could stem from this project is research into superimposition as one of the methods for the digital bone restoration. Ideally, the future work should be performed once more of the bones are identified and assembled for the later digitalization and analysis. Another thing is that a future work in creating a skeleton could look more into the joints between the printed bones. The first consideration for that would be a work with a paleontologist that would be able to decide the position and the connection of the bones to a better extent than what is done for this work. Some parts of the skeleton miss key details that would give a better idea about the anatomy of an ichthyosaur. The second consideration is the assembly mechanism itself. In this work, the parts were assembled using metal wire, and it should be better to create particular joints printed together with the details that would make it easier to assemble the bones and create a more robust connection. Unfortunately, this was an extension of this work that was beyond what is allowed by time and money.

8. References

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