Applying Reverse Engineering in the Manufacture of Water Pumping Windmill Rotor Prototype

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***Abstract*— In this research study, a Reverse Engineering technique was selected to design and manufacture a mechanical water pumping Windmill Rotor based on a commercial Windmill Rotor of 4.88m (16ft) in diameter and a tower height of 12m. The Reverse Engineering technique was accomplished in three consecutive steps: digitizing the component, processing the measured data, and creating the CAD model. By using the Deviation Analysis in the CATIA V5, all the Rotor's 3D models were affirmed by comparing them with the original scanned data. Based on these affirmed models, a final 3D assembly model was created to verify the feasibility of all Rotor components' assembly and the final approval of the design. The 3D models were the basis for manufacturing the Windmill Rotor prototype installed at a pilot site in a suburb of Tajoura. The CATIA V5 was used as an integrated system between Reverse Engineering and CAD activities for designing and developing the Windmill Rotor. Finally, from the results of this research study, one can say that the mechanical water pumping Windmill was successfully manufactured by applying the attractive Reverse Engineering technique.**

Keywords*— *Windmills, Rotor, CAD, CATIA, RE, Point cloud.

I. INTRODUCTION

Reverse Engineering is an attractive design technique in situations when a physical part or product may be without technical details, such as drawings, bill-of-material, or engineering data. RE is the process of producing a copy of an existing part without original drawings, documentation, or a computer model and capturing the physical dimension of the component [1,2]. Nowadays, RE is widely spread in various manufacturing industries. Reverse Engineering can be viewed as "the process that initiates the redesign process, wherein a product is predicted, observed, disassembled, analyzed, tested, and documented in terms of its functionality, form, physical principles, manufacturability, and assemblability" [3]. Reverse Engineering (RE) is an intensive technique that enables designer interaction to capture design intents and integrate digital data from previous products in a new product life cycle [4].

The classic multi-bladed Windmill is still being manufactured in industrialized countries, particularly in the US, Argentina, Australia, South Africa, and many more [5,6]. The most critical component of this Windmill is the Rotor, also called the "Rotor Rosette" because of its structural design. Its diameter varies between 3m and 5m, and it can have more than 18 metal sheet Sails. So the Western Windmill is still a "modern" machine of which hundreds of thousands are installed with nearly unchanged designs in many countries, i.e., Australia, Argentina, and the United States of America [5].

The key objective of this research work is to apply the Reverse Engineering process to manufacture, install, and test the Windmill Rotor prototype within a complete water-pumping Windmill. This test aims to ensure the success of the RE in manufacturing the Rotor to extract groundwater from a well designated for this research experiment. This system will target a set of future studies to improve the cost and efficiency within an intensive research project to manufacture the entire model designed to pump water in the Libyan countryside (i.e., Tajoura) in proportion to the local manufacturing capabilities. The components selected for this research work are essential for the Windmill. To obtain all the relevant dimensional data necessary to create a design drawing or CAD model, digitizing or scanning is needed. The criticality of the component often determines the precision and tolerances required to RE a component. Precision measurement devices, advanced software, and modern RE technologies have made the reinvention of mechanical parts feasible with tight tolerances and high fidelity [2].

II. RESEARCH METHODOLOGY

The methodology involves applying the RE technique to obtain the Rotor 3D CAD model and manufacturing the Rotor prototype of a water-pumping Windmill, including the various activities of the RE process of an existing classic commercial mechanical Windmill and manufacturing the Rotor prototype. The methodology's steps include (i) digitizing the Rotor components using the Baces3D portable laser scanning system to obtain dimensional data; (ii) processing the measured data, and creating the final surfaces by overlapping the point cloud with the mesh were done by performing several operations using CATIA's Digitized Shape Editor (DSE); (iii) creating the surface models of the scanned components by the Quick Surface Reconstruction workbench (QSR) in CATIA; (iv) creating the solid 3D models of the Rotor parts by the Part Design workbench (PD) in CATIA and assembling the Rotor within the CATIA assembly design workbench. In addition to (i) manufacturing the Rotor components and assembling the Rotor, and (ii) installing and testing the Rotor on a tower (12m) manufactured by Al-Anma Company on the Well dedicated especially for this research experiment in the Tajoura.

III. WINDMILLS ROTOR COMPONENTS

Emphasis was placed on implementing the Reverse Engineering technique that was adopted in this research work to manufacture a mechanical Windmill Rotor and its main components. Figure 1 shows the Rotor components, which include:

- ROTOR OR WHEEL: it converts wind energy into rotary motion.
- THE OUTER (Win 001) AND INNER (Win 002) ROTOR BANDS: they are (metallic sheets) that form the outer and inner circles for fixing the Rotor Sails.
- THE SAIL TIES (Win 003): they are the first function that controls the attack angle of the Sails, and the other function is to fix the Sails to the inner bands.
- THE SAILS OR BLADES (Win 004): the wind's power is extracted by decelerating it. However, there is a limit on how much power can be extracted from the wind.
- THE SAIL RIBS (Win 005): they fix the Sails on the outer bands and help to fix the attack angle of the Sails.
- THE CROSS TIES (Win 006): these ties are fixed on the Rotor arms to fasten the inner bands to these arms
- THE ROTOR ARMS (Win 007): these are rods with a circular cross-section to secure fixing the Sails sections on the Hub; the Rotor assembly is attached to a Hub assembly by these long arms.

The Rotor main parts are shown in Figure 1 the target for the application of the RE, except the Hub **(Win 008),** which the Al-Anma Company provided.

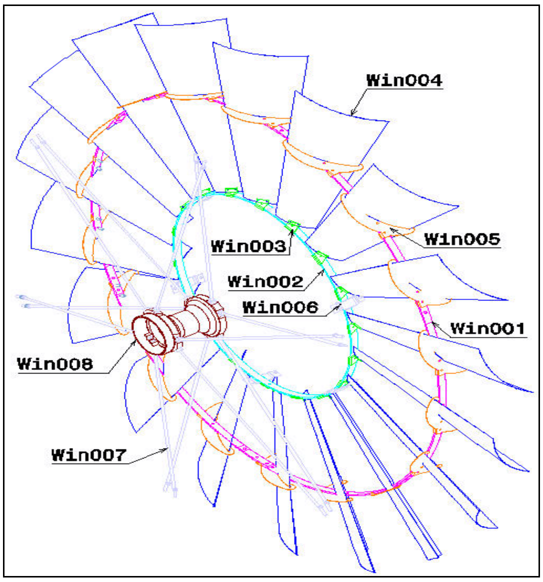

Figure 1. The mechanical Windmill Rotor components understudy.

IV. ROTOR SIZE AND SITE SELECTION

The selection of the optimal size of the water-pumping Windmill understudy for the chosen site that is intended for the RE was based on the wind profile data collected for eleven years and the site water demand [7]. The appropriate Rotor size at this site was determined in a previous study of 4.88 meters [8]. The Rotor should be tall enough to ensure it's far above the obstacles [6]. The findings of the wind energy profile analysis are as follows:

- The average daily wind speed was recorded at Tajoura and the average annual wind speed for eleven years was calculated to be 3.24 m/s.
- The location of the Windmill installation was chosen to be away from tall buildings and trees. A 12 meter high tower was also chosen to be sufficient to raise the Rotor above the surrounding isolated trees and wind turbulence.

V. REVERSE ENGINEERING PROCESS

A. Acquisition Tools and Equipment

One important endpoint of this work is the application of techniques and methodologies typical of Reverse Engineering in designing and manufacturing a water-pumping Windmill. A successful attempt has been made in this research work, which is the first time it happened in the State of Libya, as far as the authors' knowledge, to utilize wind power to extract groundwater using a mechanical Windmill manufactured locally.

It starts with the 3D scanning techniques, where one of the different types of scanning techniques was selected to carry out the dimensional acquisition operations for all Rotor components. This scanning technique was the non-contact technique using the 3D BacesSCAN portable laser scanning device (as shown in Figure 2). This device was used at Truck and Bus Company (T.B.Co). The scanned data (point cloud or mesh) were obtained from the scanner as a 3D visual sketch, but a processing for the scanned data is needed before a CAD model can be created.

Figure 2. BacesSCAN portable laser scanning system.

B. *Reverse Engineering Software*

For further modifications of the scanned surfaces and the creation of a 3D CAD model, a transformation of the point cloud from the Baces3D software into 3D software using a universal file format for data transfer (IGES) is required. Creating the final surface by overlaying the point cloud with a mesh needs a number of operations that must be made using CATIA's Digitized Shape Editor (DSE).

C. *Reverse Engineering Procedure and Analysis:*

Digitization is acquiring point coordinates from component surfaces [9]. To begin the geometric modeling of the Rotor parts subjected to Reverse Engineering, obtaining the "point cloud" in the three-dimensional space that forms the geometric representation of the digitized points is necessary. This point cloud file containing the information obtained from the acquisition device can subsequently be converted into a neutral format (e.g., IGES) or imported directly into the software used for modeling [7]. Figure 3 illustrates the general process flow diagram for the application of Reverse Engineering in this research work.

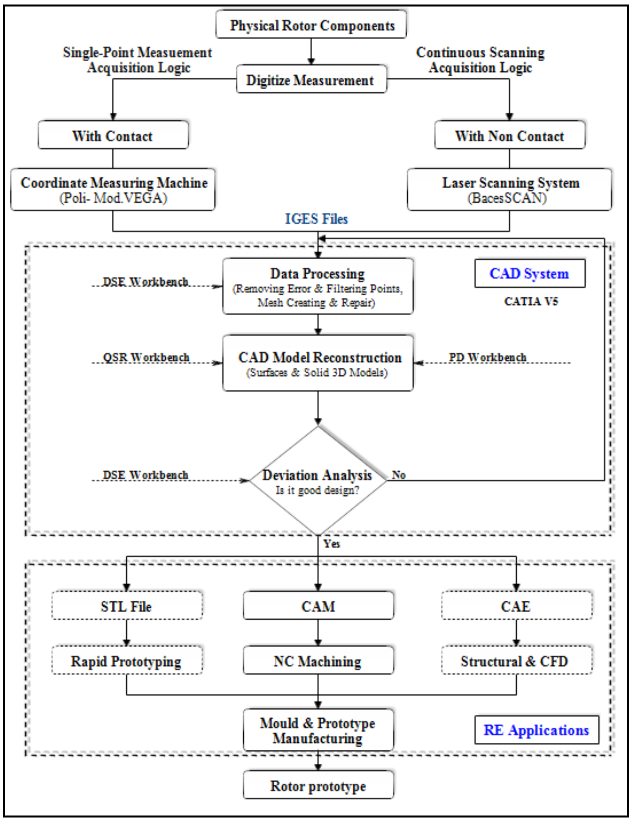

Figure 3. RE process flow

This flow diagram demonstrates some of the possible applications of the generated 3D CAD model obtained from the RE process that can be explained as follows:

a) *Scanning the physical Rotor components*

All components are precautionary painted white to avoid incorrect points caused by scanning unadjusted surfaces because of the uncontrolled laser ray scattering [7,8,10,11]. These incorrect points cause a serious problem with CAD modification, especially for rapid prototyping processes and manufacturing with NC machining. The parts have been well fixed one after the other on the prepared measuring table to prevent movement of the measured piece during the scanning process. The examination room is also dimmed to reduce errors. The scanning process was performed for all components without fragmentation (one scan or patch). In Figure 4, the BacesSCAN is shown in a moment of its use during scanning the Sail rib. The IGES format was chosen to transfer the point cloud files from the Baces3D software digitizing machine to the CATIA used to perform the point processing operations and the CAD model reconstruction.

b) *Processing the measured data*

The first two problems that arise in the 3D rendering (on the CAD system software) of a physical object being scanned are the enormous number of digitized points and the errors that any scanning operation affects. Therefore, measurement errors must be corrected as much as possible, and points that may have errors greater than the pre-established threshold must be discarded. After getting the detailed dimensions of the Rotor parts from the scan files, they were refined into a final part, i.e., the resulting measured data is cleaned up, smoothed, and sculpted to retain its required shape and accuracy by applying [7,8]; the (i) removing error points: by using the Remove command in DSE CATIA; (ii) filtering points: by applying the Filter command in DSE CATIA; (iii) creating the mesh: the command of Mesh Creation of DSE CATIA, and (iv) mesh repair: the holes in the mesh were repaired with the Fill Holes, Mesh Smoothing, and Mesh Cleaning commands under the DES workbench in the CATIA.

Figure 4. The Baces3D arm during scanning of the sail rib.

c) The CAD model construction

After repairing the digitized points, the next step is creating the curves on which the surfaces that form the geometric model of the piece were built [7,8,11]. Planar curves were created with Planar Sections command under the DES workbench in the CATIA. Figure 5 shows the planar curves that constitute the surface support on the repaired mesh. At this point, the fundamental problem is the choice of surfaces to interpolate the curves obtained to replicate the geometry of the physical component as closely as possible. All the surfaces of the Rotor parts were created by Quick Surface Reconstruction (QSR) in CATIA. From these obtained surfaces of the Sail rib shown in Figure 6(a) (as an example of one of the Rotor parts executed in this research work), a solid model of 1.5mm thickness was created using the Part Design in CATIA as shown in Figure 6(b).

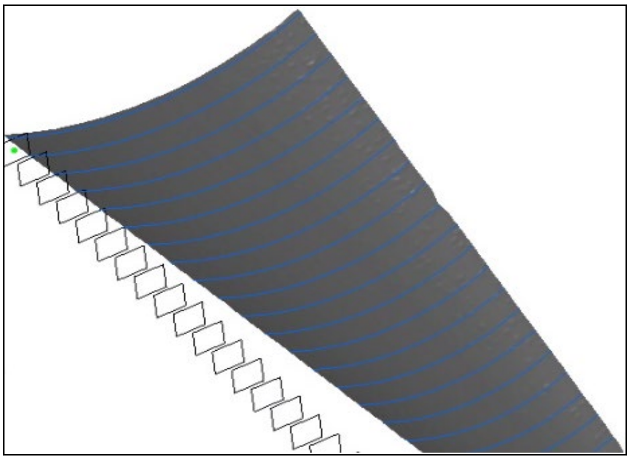

Figure 5. Planar curves on the repaired mesh.

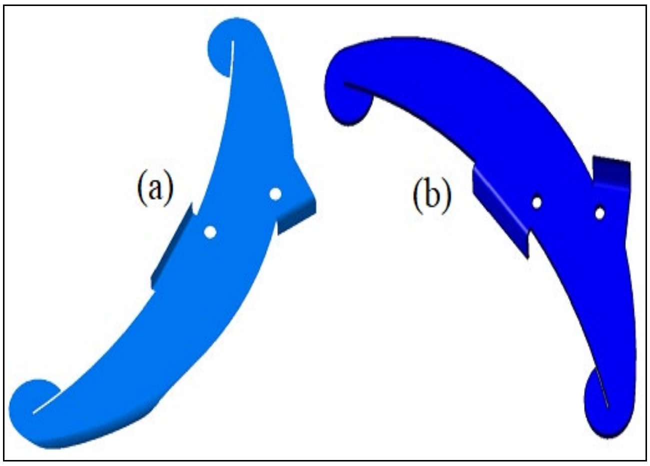

Figure 6. (a) Final obtained surfaces, and (b) solid 3D model of Sail rib.

d) The Rotor Hub

The Hub is included with the water-pumping Windmill's physical powertrain and brakes group. All the powertrain and brakes group components have been provided by the Al-Anma Company.

e) Deviation analysis results

Point cloud data obtained from 3D scanning of a part (component) was compared with the final CAD model of that part obtained by applying a Reverse Engineering technique, this comparison process is known as the deviation analysis. By using the Deviation Analysis Command within DSE, the analysis was carried out for all the Rotor components, as explained for the Sail tie. The parameters for the test are shown in Table 1.

Table 1. Input Parameters of the Sail tie Deviation Analysis.

Reference Data	Surface.1
Data To Measure	Mesh Creation.1
Accuracy	0.010
Only Orthogonal	0
Absolute	0

The results in Table 1 show that about 100% of the data points are within the tolerance limits (±1mm), with a mean and a standard deviation of 0.01, 0.03 mm respectively. Accordingly, the design is considered good and can be adopted.

Table 2. Statistical Results of the Sail tie Deviation Analysis.

Total Points	3704
Points Used in Computation	3704
Points with Positive Deviation	614
Points with Negative Deviation	397
Maximum Deviation Value (Positive)	0.15mm
Maximum Deviation Value (Negative)	-0.12mm
Mean Deviation	0.01mm
Standard Deviation	0.03mm
Positive Mean Deviation	0.05mm
Negative Mean Deviation	-0.02mm
Positive Tolerance	1.00mm
Negative Tolerance	-1.00mm
Percentage In Tolerance	100.00

One of the key outputs of the analysis is a graphical colored map shown in Figure 7.; in addition to visualize the deviation analysis data and various annotations of the Sail tie, the map shows the histogram of the data distribution, where about 81.75% the deviation values between the CAD model surface points, and the original point cloud data lie between 0 and -0.04 mm. Thus, all the components were ready to perform assembly operations using the Assembly Design in CATIA and test their ability to assemble them before starting the prototype manufacturing phase.

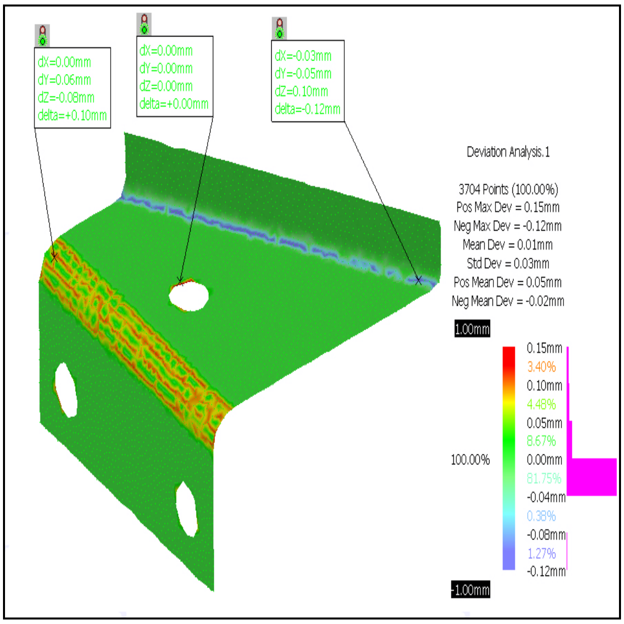

Figure 7. A snapshot of Sail tie Deviation Analysis.

f) Rotor components 3D CAD models

A 3D-CAD assembly model of the Rotor components, as shown in Figure 8, was prepared based on the existing physical water-pumping Windmill. However, Rotor assemblability verification in CATIA assembly design workbench was carried out to remove any fouling or interference in overall dimensions and to validate the 3D assembly model before manufacturing the Rotor prototype [7,8,12].

After adopting 3D models of the Rotor components because of the deviation mentioned in the earlier analysis, the two-dimensional manufacturing drawings in such a case are among the most important outputs obtained from applying the RE for the Rotor components.

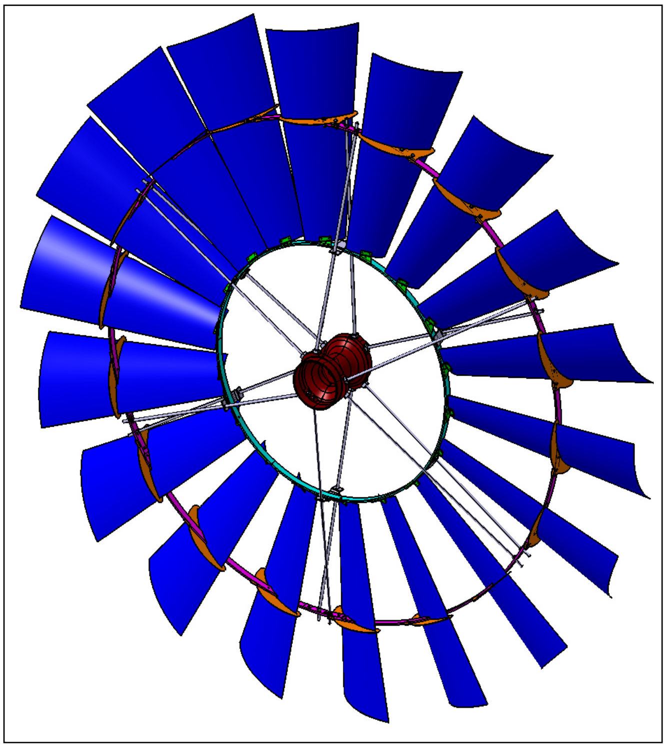

Figure 8. The 3D assembly model of the Windmill Rotor.

VI. MANUFACTURING AND PERFORMANCE TESTING

A. Manufacturing the Rotor Prototype Components

Manufacturing the Rotor prototype started with manufacturing all the Rotor components according to the requirements of the working schedule, which was prepared on the basis of the 2D drawings, as shown in Figure 9.

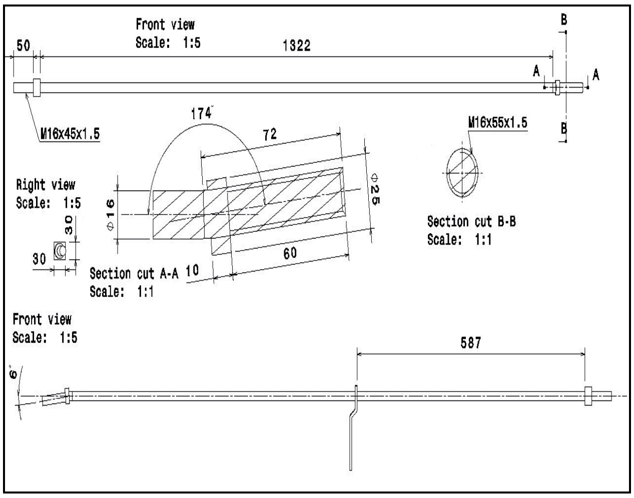

Figure 9. Complete Rotor arms 2D drawing.

Then start the Rotor assembly operations by assembling the sections of the Sails, Sail ribs, and inner & outer Rotor bands, and finally, the assembly of the complete Rotor prototype. The following pictures show details of some manufacturing processes of the Rotor components.

Figure 10 shows the process of cutting the Rotor Sail using the plasma cutting machine located at the T.B.Co. Figure11 shows the bending process of the Sail ties carried out on the bending press machine at the T.B.Co.

Figure 10. Cutting the Sails using a CNC plasma machine.

Figure 11. Bending the Sail's tie by the bending press mac

Figure 12 shows the bending process of the outer band by CNC rolling machine at the T.B.Co.

Figure 12. Bending the outer band by CNC rolling machine.

B. Sails Section and Complete Rotor Assembly

The assembly of the Windmill Rotor requires the preparation of six sub-assembly of the Rotor Sails (Sails section), as shown in Figure 13. The following pictures describe the various steps of the assembly process of the complete Windmill Rotor on the Hub; Figure 1Figure 4 (a) shows a picture during the installation of the Rotor arms into the Hub; and (b) shows the installation of the 6th Sails section.

Figure 13. The complete Rotor Sails section assembly.

C. Performance Testing of the RE Rotor Components

The actual testing of the Windmill Rotor components has been done to confirm that the Reverse Engineered components were produced successfully and fulfilled their intended function. The Windmill Rotor was installed on a tower (12m) high and was manufactured by Al-Anma Company on the Well dedicated to this research experiment.

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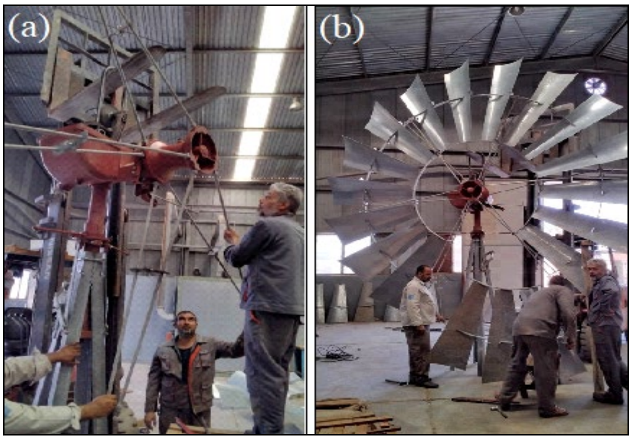

Figure 14. Installing: (a) Rotor arms into Hub; (b) the 6th Sails section.

Figure 15 shows two pictures during the installation process of the Rotor and the Tower on the Well located at the Al-Anma Company headquarters in Tajoura.

Figure 16 shows groundwater extraction from the Well by the Windmill system at the moment the picture was taken, at a wind speed of 2.7m/sec, measured at 2m from the ground. The attempt was successful, and the water flow rate was evaluated to be 1liter/10s.

Figure 15. Rotor and tower installation.

Figure 16. Extracting water from the Well by the Windmill system.

Based on the successful attempt of this research work and the researchers' recommendations, Al-Anma Company decided to completely manufacture the remaining components of the Windmill system locally by adopting the Reverse Engineering technique.

VII. Conclusions

By using digitized dimensional scanning systems to perform RE for CAD model creation of the Windmill Rotor, the researchers concluded that the RE could reduce design time and avoid errors or modifications that increase costs. Realistically, all the target Rotor components were manufactured during this research work, and the complete Windmill Rotor assembly was done successfully without any problems. Moreover, the Rotor was tested within a Windmill system's groundwater extraction from the Well at an average wind speed of 2.7m/sec, measured at 2m from the ground. The average water flow rate evaluated was 1 liter/10s. The unique thing about this research work is that it is the first comprehensive contribution of all its kind in Libya in designing, manufacturing, installing, and testing a water-pumping Windmill using the Reverse Engineering technique.

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