University of BRISTOL

Design of a 3D Object Scanning Autonomous Robot

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engineering design

SCIENCE MUSEUM

Project Objectives

To provide the Science Museum with a means of making stored exhibits publicly accessible online

The solution **must**:

- Require minimal human intervention
- Operate with a low environmental impact
- Be engaging to Science Museum visitors
- Operate in the conditions of the museum's 'big object store' without colliding with exhibits

The Science Museum 'Big Object Store'

- The Science Museum only has space to display around 8% of its exhibits at any one time
- Many exhibits in storage are located in former aircraft hangars at the big object store in Wroughton, Wiltshire. Exhibits vary in size from bicycles to civil aeroplanes
- Temperatures vary from 0°C to 25°C; light levels are low; dust, debris and oil are present and objects are placed in unordered positions

Design Overview

1. A Microsoft Xbox Kinect depth camera takes shots of exhibits from different angles. Each still image captured contains pixels having both colour and depth values
2. An Object Scanning Autonomous Robot (OScAR) manoeuvres the camera around exhibits without requiring human control.
3. A novel robotic arm allows the camera to reach heights of over 5m and lean up to 2.6m over exhibits
4. Captured data is post-processed. A software algorithm aligns the points from each camera frame in 3D space. A surface is then fitted to the point
5. 'Virtual' 3D models of each exhibit are presented to the public by means of a web-based user interface

Xbox Kinect Development

Each Kinect frame outputs a 'point cloud' - coloured points positioned in 3D space. However, a full scan of an exhibit requires frames to be captured from many different angles. Each point cloud must be aligned with those taken previously, a process known as registration.

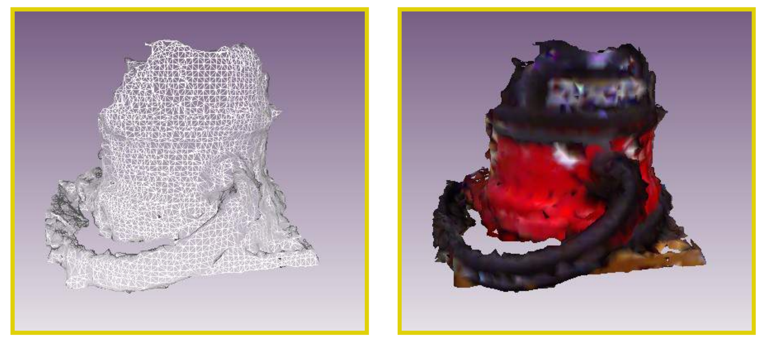
Registration

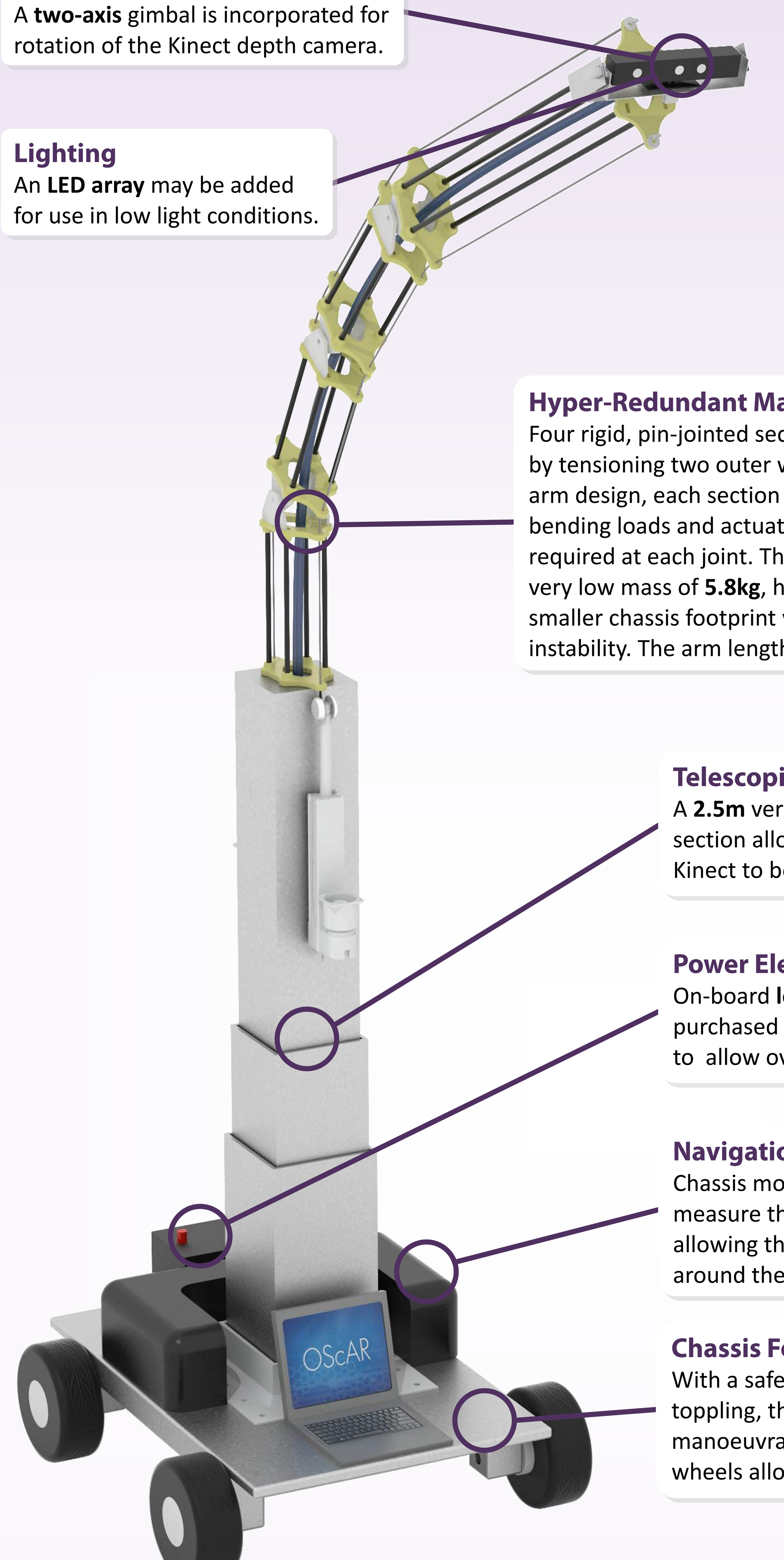
1. The established 'Iterative Closest Point' method blindly iterates to minimise positional error between clouds. This often converges on incorrect 'muddled' solutions as shown
2. An improved algorithm was developed utilising known transformations in the camera position. Tolerance analysis of the robotic arm showed the maximum error in known camera position to be **±57mm**
3. A novel two-step method was developed which further reduces alignment errors. The Iterative Closest Point algorithm is applied to the result obtained using the known camera translations

Further Processing

To produce a virtual model suitable for online presentation, the aligned point clouds go through several additional steps using open source MeshLab software:

1. Cut extraneous points to isolate subject
2. Generate vertex normals at each point based on surface approximation
3. Convert point cloud to triangular surface mesh using surface normals
4. Shade mesh panels with colour data
5. Export surfaced object





Microsoft Xbox Kinect
A **two-axis** gimbal is incorporated for rotation of the Kinect depth camera.

Lighting
An **LED array** may be added for use in low light conditions.

Hyper-Redundant Manipulator
Four rigid, pin-jointed sections are positioned by tensioning two outer wires. In the chosen arm design, each section is never under bending loads and actuators are not required at each joint. This allows for a very low mass of **5.8kg**, hence a smaller chassis footprint without instability. The arm length is **2.8m**.

Telescopic Arm
A **2.5m** vertical, telescopic arm section allows the height of the Kinect to be quickly adjusted.

Power Electronics
On-board **lead-acid batteries** can be purchased at low cost with capacity to allow overnight operation.

Navigation
Chassis mounted **ultrasonic sensors** measure the distance to obstacles, allowing the robot to navigate around the perimeter of an exhibit.

Chassis Footprint
With a safety factor of 2 against static toppling, the chassis is just **1.0x0.8m** for manoeuvrability in tight spaces. Omni wheels allow sideways movement.

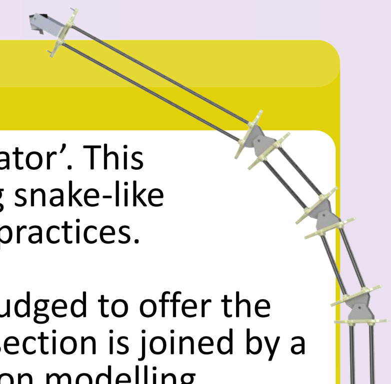
User Interface

Key areas of the user interface for viewing online exhibits were developed using a framework adapted from models of learning and meaning. The framework considers five aspects that influence the effectiveness of a person's online experience: **person → purpose**, **process**, **people**, **place** and **product**.

The OScAR audience was segmented into five categories of users, and interface features that meet the need of each group were identified (shown in the table below). This analysis inspired an innovative object-orientated approach to display the objects that is flexible to adapt to future needs and behaviours.

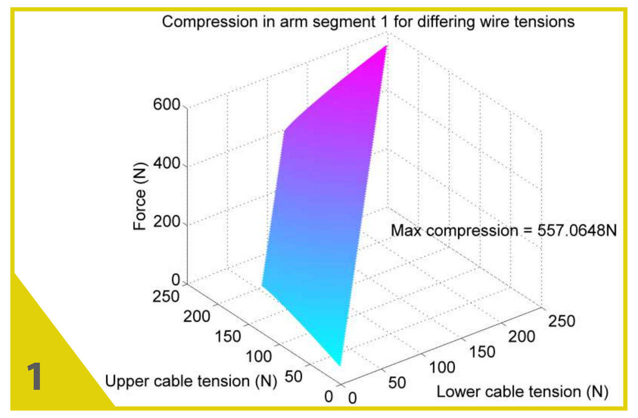
	User Categories				
User Interface Features	General Public	Website Visitor	Casual Browser	Learner	Expert
Advertising and awareness: maximise number of website hits	•	•	•	•	•
Access: design for website and mobile interfaces	•	•	•	•	•
Visual appeal: striking images linking to 3D models	•	•	•	•	
Ease of use: image driven navigation and familiar controls		•	•	•	
Links to social media networks: rating and sharing of objects or categories		•	•	•	•
Layers of information: build up detailed text and link to external sites		•	•	•	•
Choice and control: object control and category creation			•	•	•
Personalisation: user accounts with interests and history				•	•

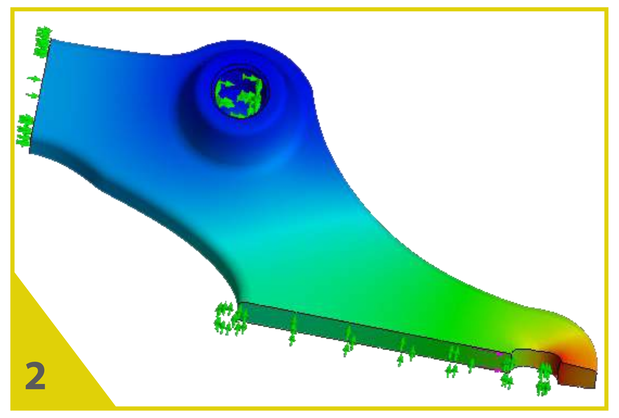
Robotic Arm Development



Chosen for its low weight, the upper robotic arm is a unique 'hyper-redundant manipulator'. This articulated structure has more degrees of freedom than are directly actuated, providing snake-like motion. The design was developed using modelling techniques as well as best industry practices.

The length of each section is provided by roll wrapped carbon fibre tubes. These were judged to offer the best compromise between cost, weight, stiffness, strength and ease of assembly. Each section is joined by a PMMA and ABS plastic 'vertebra', optimised for rapid manufacture using fused deposition modelling.





Maximum effective predicted stress	2.2 MN/m^2
Maximum predicted deflection	1.8×10^{-2} mm

Force in Structure

A statics model was developed to predict the arm position and forces within it, given the two wire tensions (1). The maximum loads in the structure were found to be:

- **557N** compression in a section
- **125N** resultant on a vertebra as the tension wire bends around it

Finite Element Analysis

Knowing the expected loads, a SolidWorks FEA model was constructed to ensure the vertebrae components were sufficiently strong. Force-displacement testing validated the FEA model, with only **8.4%** variation from calculated results.

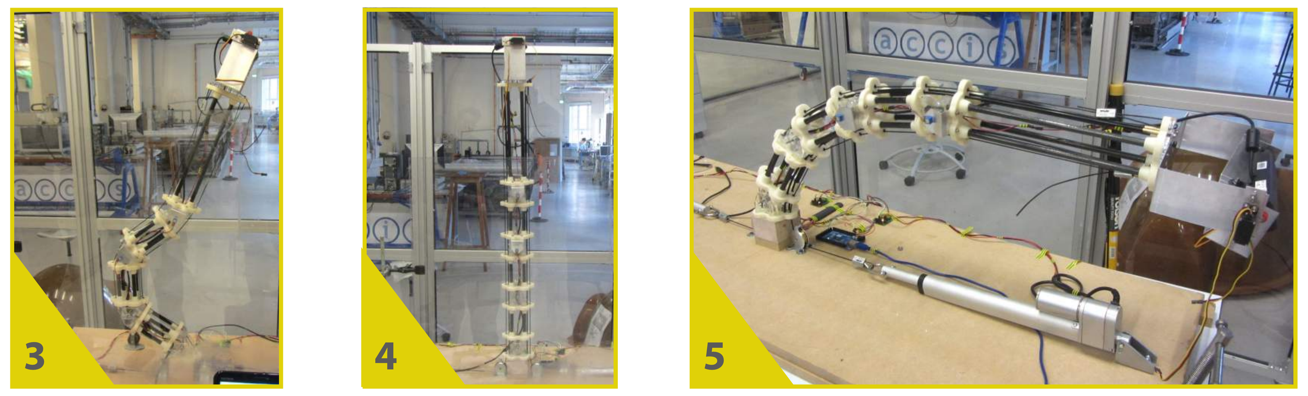
Buckling Strength

The carbon tubes withstand expected axial and buckling loads with reserve factors of **1.4** and **20** respectively.

Prototype Development

A 1:4 scale prototype was constructed to validate the operation of the arm.

- Initial tests found that the arm could not be supported by the tension wires alone - each joint collapsed until resting on its endstops (3)
- This unexpected behaviour was identified as being a feature of the joint geometry
- An elastic fibreglass backbone was added, supporting the arm mass and constraining it to a curve shape. This resolved the problem. (4, 5)



See it in action!
Use the QR code below to view a video of the prototype on your phone

Business Case

Market Need

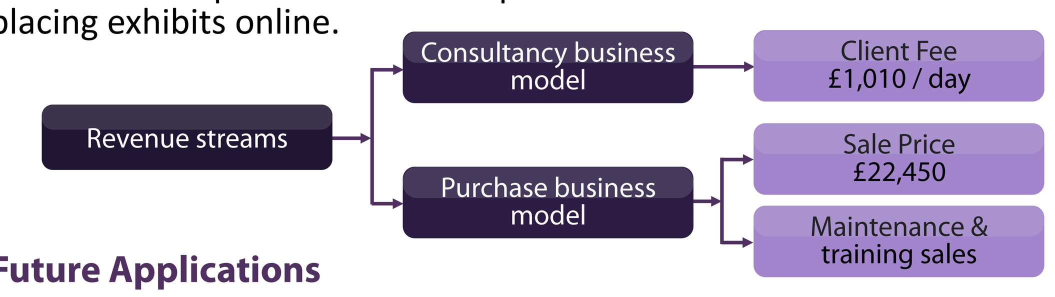
- 51% of museums experienced a budget cut between 2011-2012
- As a result, 400 UK museums were forced to partially close
- Museums facing closure could use the OScAR system to maintain public access whilst reducing operating costs

Financial Projections

- **£70,000** development cost
- Payback period = **12 months**
- **40%** net profit margin

Sales Strategy

Two sales models have been derived to target different customers. Prices are competitive when compared to alternative means of placing exhibits online.



Future Applications

The OScAR system may be adapted for different applications, such as:

- Visual Inspection of structures
- 3D data capture for film and video game production
- Military and disaster zone use
- Augmented reality and gesture-based interface use

Conclusions

A system has been developed to make Science Museum exhibits accessible online with little human input and low energy use.

- A bespoke software algorithm allows objects to be displayed in 360° from frames taken using a low cost Xbox Kinect camera
- A robotic arm can position the camera at heights up to 5.3m and horizontal distances up to 2.6m. A lightweight design allows a small chassis footprint of 1.0x0.8m for manoeuvrability.
- Suitable features have been proposed for the User interface
- A strong market need suggests that the £70,000 development cost for the system will be paid back in 12 months

Future areas of work

- Integrate arm control system with image processing algorithm to give Kinect position
- Modularisation of system components to increase sales potential.
- Increase design robustness for outdoor use including in military and disaster zone areas