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ICEDIG.EU *Innovation and consolidation for large scale digitisation of natural heritage*

D3.8 R&D in robotics with potential to automate handling of biological collections

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Abstract

This report investigates the current state of physical (mechanical) robotics, automated warehousing approaches and assistive technologies in relation to the storage, handling and digitisation of natural history collections.

While ‘robots’ may sound futuristic, there are many existing examples of automation in the natural history and cultural heritage sectors, and this is growing rapidly. While purely software-based automation is outside the scope of this paper, hardware in use includes everything from barcodes and conveyor belts for digitisation; to imaging technologies that need not always be supervised; robots that handle multiple vials for molecular and genetic work; and use of robots in display / exhibition contexts e.g. for 3D printing. While automated storage and retrieval have not yet been applied in natural history collections (to the best of our knowledge), several case studies of automation from e-commerce and the library sector are explored in this study, as well as examples of robotic arms in the heritage sector.

Robots and other automated systems are very good at repetitive tasks, and are developing rapidly to be able to handle more complex object types, at a lower cost. High volume, high variety of objects, and considerations such as fragility are not unique to the natural history sector - they apply for example to major retail operations - however natural history collections do offer some of the more extreme examples of these challenges, and in particular are not replaceable in the way many other objects can be. Business cases for automation in our sector also need to take into account that our processing times are often not critical in the way they can be for commercial operations, although they are becoming more so, particularly in digitisation and as our resources continue to be limited - digitisation on demand is likely to come with expectations about response time, for example.

Besides automation of object handling and imaging, warehousing automation can improve retrieval times from storage, space efficiency and climate control. However, implementation of automated warehousing solutions would require significant adaptations of existing storage space. This option may be of greater interest when new storage spaces are being built, and there may be the opportunity to move to more standardised storage units that can more readily be handled automatically.

At this time, a fully automated solution from storage to imaging and back to storage is not realistic for the complex context of natural history collections. By developing independent components (including storage & retrieval, transport, object picking, and imaging) which can be connected in the future, progress can already be made towards an end-to-end solution.

The natural history sector will need to work with suppliers and subject matter experts, including innovative smaller companies, because they have the required expertise to develop and integrate components. These suppliers will need to be provided with clear requirements and information if they are to understand our requirements, perhaps through shared research and development approaches and piloting.

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DiSSCo, and its Centers of Excellence, could play a further role in developing the expertise to better communicate with SMEs. Also, DiSSCo can lead a concentrated effort for research and development in this field, to make sure that the various pilot projects are aligned.

Institutions holding natural history collections are likely to find many potential uses for automation, each with their own specific business case that will need to be developed - in this context, it is particularly important to consider the desired outcomes, including e.g. the benefits to humans of automating more repetitive aspects of their work.

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Introduction

Goal

Global natural history collections are estimated to contain 2 to 3 billion specimens worldwide and 1 to 2 billion in Europe, of which 3% (at best) were accessible through GBIF in 2010 (Ariño, 2010). Rough calculations were made of time and cost for imaging and databasing the global natural history collections, resulting in the staggering numbers of €150 billion and 1500 man years (Blagoderov et al 2012). Manual handling of specimens is the largest contributor to the high cost and time. Introducing robotics could help decrease processing time and costs, and alleviate problems with regard to health and safety in both digitisation and the wider storage, retrieval and handling of specimens. The goal for this report was to produce requirements and recommendations that can support practical consideration and further R&D and pilots, by collections and suppliers - although this has proven difficult owing to lack of industry engagement, this report offers discussion and suggestions for collections considering the use of robotics and automation. Where needed, this task has drawn on the assistance of subcontractors with knowledge of innovative technology.

The topic of robotics and automated warehousing is very broad. While we need to look forward to relevant developments in the foreseeable future, we need to bear in mind that these can be hard to predict - perhaps the most important element going forward will be to remain flexible and open to these opportunities as they continue to develop and as their costs continue to fall.

Definitions and scope

For the purposes of this report, 'robotics' and 'robot' refer to physical (mechanical) constructions with electronic and software components, designed to replicate certain human actions with a degree of autonomy.

Robotics is a form of automation - technologies that reduce the need for human intervention in a vast range of processes. Factory or warehouse automation often uses machines to perform highly repetitive and standardised tasks, sometimes boringly simple, sometimes highly complex, with processes for identifying and handling exceptions e.g. by alerting a human operative. Due to their use of sensors to interact with physical objects, and often to being reprogrammable, robots are often associated with greater versatility than other automated machines. For this report, we use 'automated warehousing' and 'automation' to refer to the range of technologies that allow mass processing or the management of a large environment, for instance retrieval of collections objects from a warehouse (often using mechanical components that do not resemble humans at all); and 'robotics' to refer to more 'human' processes such as the handling of an individual specimen (e.g. by a robot 'arm'); however, these are not hard and fast distinctions - for example a

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robot arm is usually capable of more than human movements e.g. greater rotation, and robots may be part of the automation solutions in a bulk processing environment.

In addition to robotics and automated warehousing, this report touches briefly on assistive technologies, particularly those such as 'exosuits' that are designed to assist with, and reduce risk from, handling or lifting large, heavy and awkward objects.

The terms robotics, robot and automation are also now frequently applied to process automation using software, without any mechanical or physical components. Software automation is outside the scope of this report. Other tasks and reports within ICEDIG and SYNTHESYS+ address the use of software automation in relation to specimen digitisation and the extraction of data, including ICEDIG Task T4.1/D4.1 **(doi:10.5381/zenodo.3364502)** *Methods for Automated Text Digitisation* (Owen et al 2019), and the SYNTHESYS+ Joint Research Activity *Specimen Data Refinery*. Software automation is already in use across many aspects of digitisation, including image processing, batch quality control, barcode detection and image segmentation (e.g. ICEDIG T3.1.5/D3.2, Allan et al 2019, Hudson et al 2015, Summerfield et al 2019).

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Robotics and Automation in Natural History collections – discussion

The case studies in the next section of this report offer particular examples of the uses of robotics and automation in our own and other sectors. This section provides a more general discussion of the strengths and limitations of robotics and automation in relation to Natural History Collections handling, storage and digitisation; a summary of key hardware; and discussion of how collections might assess potential solutions and the business case for using automation in their particular circumstances.

Process components for retrieval, digitisation and imaging

At this time, a fully automated solution from storage/retrieval to imaging (or other uses) and back to storage is not realistic for the complex context of natural history collections, and may not always be needed. By developing independent components which can be connected in the future, progress can be made towards an end-to-end solution (see Figure 1 and Table 1).

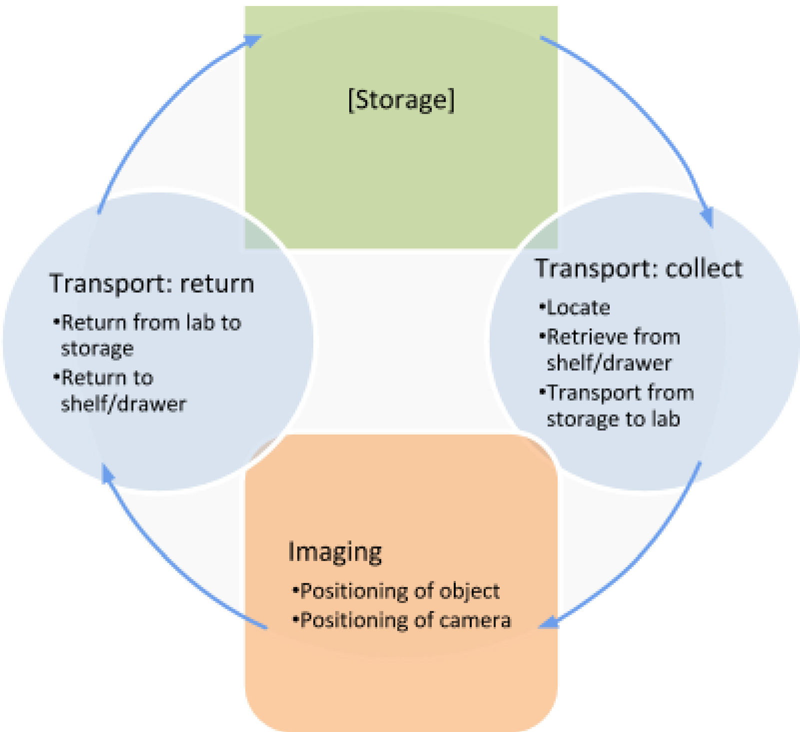

Figure 1 Possible end to end process of storing and imaging natural history objects for automation.

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Table 1 Components of automated system for storing and imaging natural history collections with some possible solutions and impediments to be solved - NB this is illustrative not exhaustive and it is likely that there are more potential solutions and limitations. Component are represented by colour, matching figure 1.

Step	Potential automation solution	Dependencies/limitations
1. Locate in storage	Physical location known in database	Ideally every object needs to be in database, to programme physical finding
2. Retrieve from shelf/drawer	1. Object picking robot 2. Retrieve whole shelf/drawer for human picking at a central point	Ability to operate the shelving units, and accommodate relevant objects.
3. Transport to lab	Mini self-driving robot	Needs to be safe for humans and collections. Needs to navigate existing space.
4. Pre-imaging processing	Object handling robot	Handling of specimens and labels
5. Positioning of object for imaging	Object handling robot	Handling of specimens and labels
6. Positioning of camera for imaging	Automated imaging station	Safety of object
7. Post-imaging processing	Object handling robot	Handling of specimens and labels
8. Return from lab to storage	Mini self-driving robot	See steps 2. retrieval and 3. transport
9. Return to shelf/drawer	1. Object picking robot 2. Return whole shelf/drawer for human handling at a central point	Ability to operate the shelving units, and accommodate relevant objects .

At its simplest, automation can refer to storage that is controlled electronically - for example where we have remote control of environmental conditions such as temperature and humidity that could be described as automation. The BBC archive in Perivale[1] uses automated compactors in their master film store - this is a cold store for flammable cellulose nitrate film, and automation allows for the position of the compactors to be standardised every night to ensure equal cooling throughout. This solution is not used in their other archive vaults, however, because these are subject to greater use and there is a high risk of system problems and breakdown if dust or debris get into the runners.

Automated warehousing with automated or partly-automated retrieval is more complex - this requires every relevant object to be identifiable, ideally with the physical location in a database. This can be at the object level, or per systematic category (based on taxonomy, geography and other used categories in NH collections) at either shelf or shelving unit level. Machine readable barcodes (or other solutions such as radio-frequency identification -

[1] Visited by Helen Hardy & Laurence LIvermore, January 2020

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RFIDs) at object and/or storage container level would increase the effectiveness of such a system.

Due to the great variety of natural history collections, multiple automated imaging systems are likely to be needed. In this case imaging automation of natural history collections needs to be split along more than taxonomic lines alone. In assessing digitisation costs for outsourcing, the Smithsonian's National Museum of Natural History considers approximate object size; volume/dimensionality (is it flat or not); quantity of objects to be processed; and degree of complexity in the handling required e.g. whether objects can come straight out of storage to imaging, or require e.g. conservation or curatorial interventions[2]. These are all likely to be equally relevant criteria in considering the possible application of automation to the workflow stages above, as is preservation type.

Robotic object handling

> *'...it's worth remembering that nothing stumps a robot quite like a bag of oranges. They just can't deal with it. The bag moves in too many weird ways, there are no obvious bits to grab hold of, and if you squeeze too hard you end up with orange juice instead. '*
> *https://www.theverge.com/2018/5/8/17331250/automated-warehouses-jobs-ocado-andover-amazon*

Industrial uses of robots and automation highlight a number of key strengths and limitations that apply across sectors[3]. Robots are good at repetitive tasks - while they may wear out, they can typically carry out repetitive tasks numerous times, at high speed, without breaks or risk of injury. Many of the steps in table 1 above involve repetitive elements, such as taking containers in and out or pressing a button to take an image.

In relation to handling of collections, however, the quote above is highly relevant. Natural history collections can be a challenge for robots because there is very little that is standardised between collections (within or between institutes) and even within one type of collection. The specimens are fragile, don't necessarily stay put in one place on a flat surface, and can also be soft and limp.

For example, the picking of pinned insects by the pin is relatively easy for humans, but a roboticised solution is not yet available which can ensure the integrity of the specimen. In this example with pinned insects in a drawer, the robot needs to identify a specimen, locate its pin, grasp it at a suitable point (clear of specimen and labels) with the correct amount of pressure, lift and move carefully. Then a suitable location for placing it needs to be identified

[2] Source - NHM London visit to Smithsonian December 2019

[3] Examples can be found at :https://www.themanufacturer.com/articles/what-does-the-automated-warehouse-of-the-future-look-like/
https://www.whichwarehouse.com/blog/news/automated-pick-pack-operations-strengths-weaknesses/
https://www.theverge.com/2018/5/8/17331250/automated-warehouses-jobs-ocado-andover-amazon

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(empty, suitable surface) and place it with the pin still vertical with the correct amount of pressure. Experts from Eindhoven University of Technology commented that identification of a single specimen is still a challenge, as long as the specimens aren't regularly spaced out in a grid, and certainly overlap of specimens would be an issue for robotic identification (e.g. butterfly wings). Subsequent manipulations, such as removal of labels or placing in a specific orientation would be even harder.

Because these challenges exist in other industries, however, progress in robotic development is swift and robotic handling is increasingly becoming more sophisticated, for instance using computer vision with sensors as input, and a variety of physical handling solutions (see 'grippers' below).

Another factor to be addressed in relation to specimen handling is stakeholders' opinion. Institute management and collections staff need to support the notion of automation and robotisation of imaging and storage workflows, a substantial change. Systems will have to be trialled and demonstrated before risks are likely to be seen as acceptable. However, the head of a major R&D institute developing an automated 3D digitisation system for heritage and industry has noticed that many collection holders are becoming more comfortable with the idea: for example digitisation technologies such as conveyor belts are now commonplace (P. Santos, pers. com. See also section on CultLab3D).

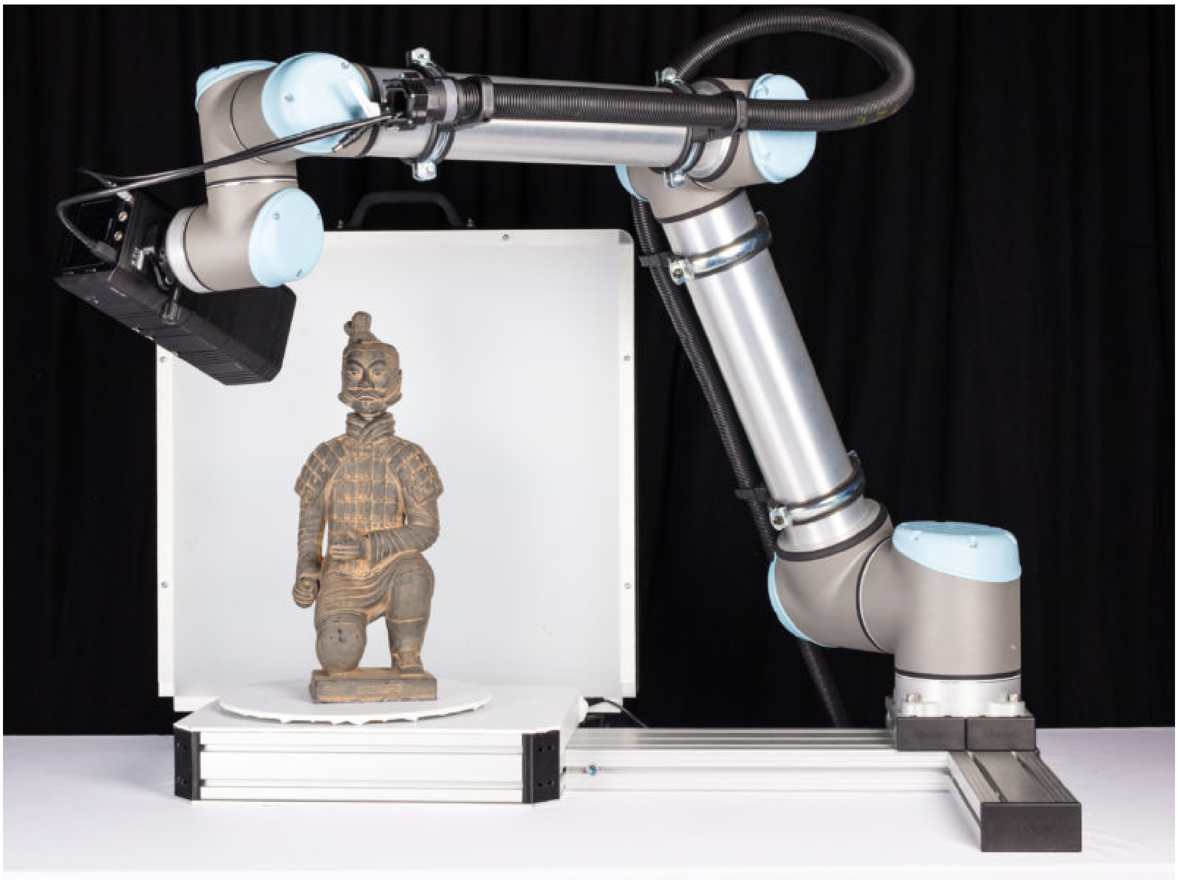
While direct robotic handling of natural history specimens may not currently offer an acceptable balance of risks and costs against benefits, there may be greater potential in relation to indirect handling, i.e. handling storage containers/units such as drawers or jars. At present, standardisation of storage is often limited, though not as limited as standardisation of specimens. Historic collections and object variety often mean a wide variety of storage, e.g. jars of all sizes, shapes, sealants etc. There may also be limitations such as drawers which may be slightly jammed, uneven navigation routes, or where steady movement is needed to keep the contents from shifting (although robots can be steadier than humans in some circumstances). An alternative is to increase standardisation with robotic handling in mind - this involves higher cost and effort before adoption of the automation, but may be suitable when collections moves and rehousing are required for broader reasons.

Summary of key hardware

Hardware for automation is developing rapidly. Some specific examples of relevant technologies are included in detail in the case studies below. Some of the most relevant current hardware solutions include robotic 'arms' and grippers; conveyor belts; and exosuits. The cost, precision, reliability and ease of implementation of these hardware components is key to the success of automation. In general, the abilities of this hardware continue to increase (e.g. precision of handling) and their costs to fall.

Robot arms

Robot arms are currently available off the shelf at various performance levels and prices. For handling small to medium specimens or storage units, payload is of lesser importance. Precision, safety features, degrees of freedom and ease of programmatic control are probably the key elements. However, full account should be taken of the expected load e.g. a professional camera with macro lens, macro extension tubes and lights, as well as the required reach (depending on the size of the specimen the arm needs to move around).



Example of robot arm with a camera. The object is placed on a surface or turntable, and the robot does not physically interact with the object. Source: https://www.cultlab3d.de/index.php/2018/09/29/cultlab3d-is-at-photokina-in-cologne/

Robot arm options and features

"A relatively new trend in robotics is the development of collaborative robots, or co-bots. Co-bots, which are designed to work safely with humans, are becoming more commonplace in industrial manufacturing applications. The top four major industrial robot manufacturers, (ABB,

Bosch, Fanuc and Kuka) are following start-up companies such as Rethink Robots and Universal Robots in development of co-bots. Collaborative robots use safety-rated sensors, allowing an operator to work in the same space as the robot and share tasks without fear of injury. As prices for these safety-rated sensors drop, the trend is reflected in the cost of co-bots. *The price of industrial robots has dropped more than 25 percent since 2014, and is expected to drop an additional 22 percent by 2025. Today, an industrial robotic arm can cost anywhere from $25,000 to $400,000. When looking at the cost of an industrial robot system, other peripherals like controllers, a teach pendant, end of arm tooling (EOAT) and software must be considered as well. Once these application-specific peripherals are added, total system costs could double. In some cases, purchasing a used or refurbished robot or system can reduce the price as much as 50 percent. Robots for schools, universities and other non-industrial applications can be found for $1,000 or less, but these robot arms are not suited for industrial applications.* *The largest factors involved in determining cost are robot size (reach), number of axes, application, end of arm tooling (EOAT) and safety components. In general, the bigger the reach and the larger the payload, the more the robot will cost. However, application-specific peripherals and safety components, such as collision sensors and safety cages, also contribute to the price of an industrial robot system."*
From: https://insights.globalspec.com/article/4788/what-is-the-real-cost-of-an-industrial-robot-arm (accessed 25-09-2019)

Safety for objects and humans

Traditional robot arms often are surrounded by shields on multiple sides, to ensure the safety of humans in the vicinity. If human loading and unloading is needed, this is often achieved by having the "safety cage" on three sides and a sensor (e.g. light screen or motion sensor) on the fourth side. Further, they can be equipped with collision sensors. Collaborative robots are equipped with safety features such as collision detection or force feedback. When unexpected force is detected, the arm stops operating. Specific models will freeze their position at this point, others will release all joints causing the arm to "collapse". Other safety features include a programmatic bounding box for operation to define where the arm is not allowed to come and emergency switches. Collaborative robots are also safer due to the lower speeds at which they move.

Grippers

A robot arm can be equipped with a range of end effectors (also called end of arm tooling, EOAT) of which grippers are a likely tool for handling specimens, containers or equipment such as cameras. In industry spray guns and power tools are commonly used, as well as various specially designed end effectors. Grippers can for example be two opposable "fingers", vacuum and suction pads, and computer-controlled magnets. Replicating the dexterity and flexibility of human hands is a known challenge, especially when multiple 'hands' work together. To pick up specimens, grippers either need to sense / be programmed

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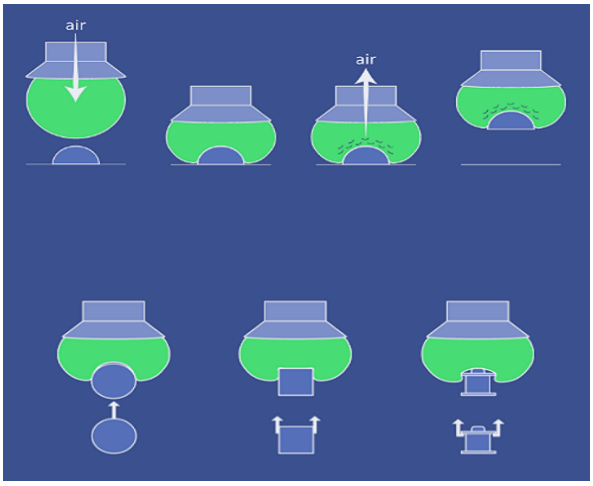
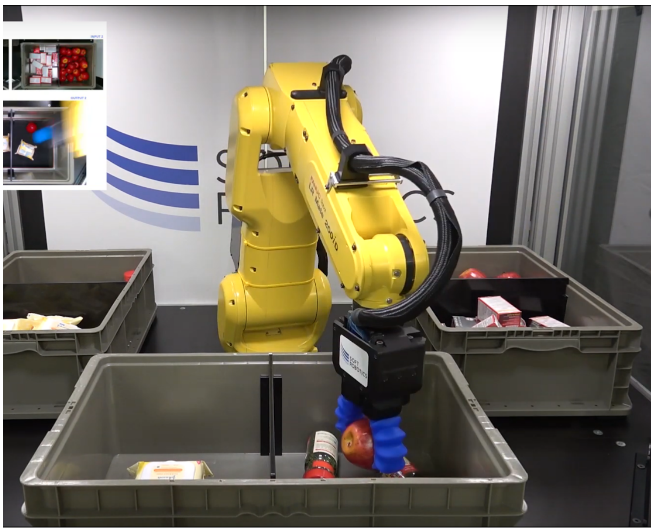
for factors such as the weight, shape and slipperiness of objects, to apply the correct amount of force and prevent slippage and crushing, or need to deploy types of grip that by nature are less likely to cause damage. The former offers greater precision, however the latter appears to be more straightforward to achieve.

The field of soft robotics is potentially of great interest in this context, as it deals with developing robots that are soft, flexible and compliant, as opposed to rigid. This allows the grippers to interact with objects that are pliable and of varying shapes. Part of the research is in fact mimicry, copying nature for industrial purposes. An example of mimicry in soft robotics is *m*Grip designed by Soft Robotics Inc[4]. This gripper can interact with objects of high shape variability without need for computer vision systems or pre-programming (at least for grasping, less for sensing the context of objects around it), through controlled pressure of the air in the tentacles of the gripper, they form around the object and grasp it.

Another specific type of gripper capable of dealing with a high variety of object shapes involves a flexible membrane filled with granular material, called the granular jamming gripper, developed by Empire Robotics under the name VersaBall[5] (Amend et al 2016). This specific design allowed the gripper to form gently around the object (unjammed, fluid-like state), after which the air is evacuated causing the granular material to become jammed in that specific shape, gripping the object softly. Release of the object is achieved by releasing pressurised air into the gripper. However, in 2016 Empire Robotics closed its doors due to not having been able to fully commercialise the product.



Schematic view of Versaball in action. Source: https://3dprint.com/162151/versaball-lessons-learned/



Soft Robotics gripper, still from video (00:41) just before release of object. Source: https://youtu.be/Pxd5-ZD9XcQ

In a video of the Soft Robotics' *m*Grip in action, a robot picks various objects from bins and places them in another. Grasping and lifting is done without issues, but the video

[4] https://www.softroboticsinc.com/mgrip
[5] https://www.empirerobotics.com/products/

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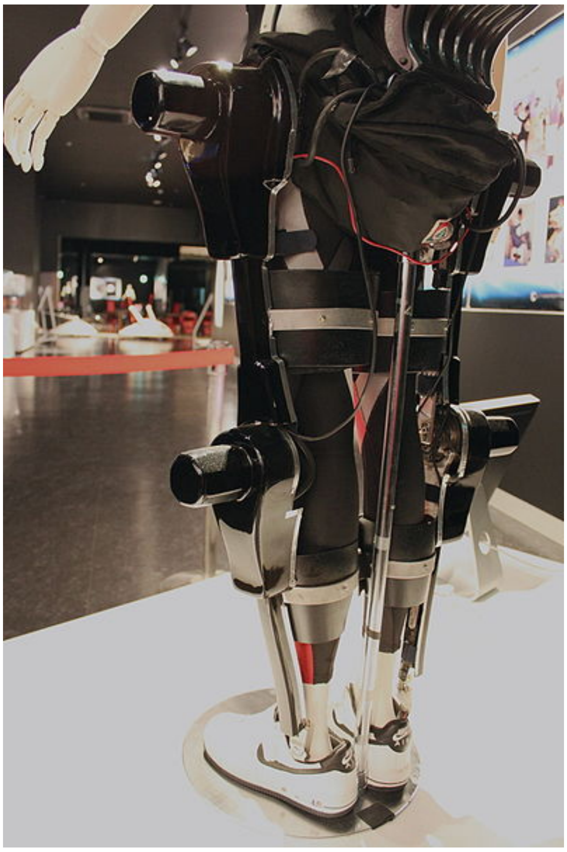
demonstrates the complexity of the requirements for handling natural history specimens: the apple is released a few centimeters above the bottom of the bin, on top of other objects (see image).

Exosuits

Exoskeleton technology comes in various forms, targeting various movements, body parts and actions. Some are powered, for the use of sensors and actuators, while passive exoskeletons can provide weight redistribution and shock dampening. These and other assistive technologies have often been developed for medical or military uses, but are coming to be used more in industry to support human operatives and avoid injuries such as back injuries and repetitive strain injuries. We are not aware of any current uses of these technologies in our sector, however they may be relevant to some of the Health and Safety risk management elements discussed above, particularly if warehouse-type environments become more common for collections storage. In effect, they are an extension of the principles of current Personal Protective Equipment such as masks and helmets, and of technologies such as forklift trucks that help with lifting.



An example of an exoskeleton suit.
Source: https://commons.wikimedia.org/wiki/File:Hybrid_Assistive_Limb,_CYBERDYNE.jpg

Managing and mitigating health and safety risks

A key benefit of robots in industry is that they can manage many operations, particularly repetitive tasks and those involving objects or environments that pose risks to humans, with much lower chance of injury or damage than human operators. To understand a risk-based approach to assessing the benefits of automation for natural history collections, the Natural History Museum London (NHM) analysed their Health and Safety risk management system - the detailed outcomes and methodology are at Appendix 2.

Across discussion with the NHM Health and Safety team, and analysis of relevant risk categories and risk assessments, key risk areas fell under the broad categories of manual handling; broader environmental factors; and working alone. There is scope for automation to mitigate risks across these areas, although there are also some risk categories where the risk to robots is equivalent to or higher in severity than the risk to humans. In all cases, the usefulness of automation to mitigate risks depends on the desired outcomes (e.g. acceptable risk level) and on cost-benefit analysis relevant to the particular circumstances (see next section).

Assessing potential automation solutions

While this report makes a range of general points about automation technologies; their potential applications and limitations in our sector; and some case study examples; in practice any individual institution will need to consider their own specific context and challenges; and the costs and benefits of specific options in relation to these. This section offers some key areas to consider.

1. **Define your problem and aims**
   The costs, benefits or risks of automation will be highly dependent on the challenges you face and the desired outcomes. Automation is often perceived as a time and/or cost-saving technology, and this may indeed be key - for example institutes considering new storage facilities may aim to minimise their future resource costs by examining the scope for automated retrieval of storage units. There are, however, a variety of other aims to which automation may be relevant - for example managing key operational risks (health and safety; security); increasing speed e.g. in performing digitisation; and 'freeing up' increasingly scarce human resources to focus on higher value, more rewarding activities that may increase wellbeing. It is important to establish the criteria against which you are assessing automated or other solutions.

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2. **Understand the options**

   The speed of change, and lack of previous application of many automation solutions in our sector, are likely to make engagement with suppliers and tests, trials or pilots essential. Engagement with the robotics industry may require support for both sides (see Specifications section below), for example *via* programmes such as DiSSCo, or government schemes to support innovation.

3. **Understand the business case**

   Understanding whether an automated solution is the right one involves some relatively complex cost and benefit comparisons. It is often the case that automation may come with relatively high ‘up front’ costs, for example, a robot arm may have a higher cost than employing a human operator over the first year; but this balance may shift when factors including working time, risk of injury, recruitment/replacement costs and so on are taken into account, and where costs are looked at over a longer period. As with any project involving capital equipment, costs over the expected lifetime of this kit and depreciation should be taken into account. Use of automation may be part of a wider business case, e.g. it may be that cost savings of new storage per square foot can only be realised if storage at height can be used with automated retrieval. One very critical factor here, which is key to the fact that automation may often not be cost-effective currently, is our ability to ‘feed the robots’ - in other words for human steps in the process such as readying collections for digitisation to keep up with the automated capacity and realise those benefits - although it should be noted that this also often applies to e.g. imaging by humans, which can be faster than the curatorial steps around it. Currently, it may often be the case that the costs of automation outweigh the benefits - however this is likely to continue to change rapidly, and particularly where institutions are undertaking major changes to collections such as moves or mass digitisation it is worth revisiting the business case regularly, and trying to retain flexibility to future automation options.

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Case studies

Case study 1: Automation of herbarium sheet digitisation

Please note that a full description of these solutions can be found in the report of ICEDIG Task T3.1.1/D3.6 on digitisation of herbarium sheets.

Herbarium collections provide the best examples of automated mass digitisation incorporating both physical and software components, as there are currently two of these solutions (by Digitarium[6] and Picturae[7]). These systems still require handling by human operators to load and unload, to apply barcodes, and to detect special specimens such as types and specimens requiring restoration. Specimens are loaded onto a conveyor belt system, which automatically moves a series of specimens through an imaging station. At the end of the line a human operator unloads the specimens. Image adjustments (including colour correction, potential sharpening, cropping, etc.) and file naming through barcode detection are done automatically. After quality assessment the batch of specimens is ready to be returned to storage. To achieve the highest speed it is important that as few as possible human actions are required: any positioning and adjustment of labels slows the process down. These systems have been tested as being 4 to 5 times faster than one at a time scanning of herbarium sheets - however a key barrier to achieving these imaging speeds is the ability to have specimens ready for this process in sufficient volume (e.g. pre-curation). This issue is associated with storage optimisation, which in some instances could greatly increase the speed of retrieval and replacement.

The human component in this process is the loading and unloading of specimens and detecting special cases. Sometimes a specimen has associated material in an envelope, which can be opened into trays to be imaged as well. It is essential that any loose material and labels stay together. The fragility and special attention to loose material currently mean that human involvement cannot currently be replaced by automation.

The conveyor belt component of these solutions could be used to automate digitisation workflows of other collections. It has indeed already been applied to pinned insects (Tegelberg et al. 2014; Tegelberg et al. 2017). Herbarium sheets are more standardised and nearly two dimensional, which makes it easier to automate digitisation. Issues such as depth of field and positioning of an object taking into consideration stability, standardised anatomical and diagnostic views are greater when objects have greater depth. Still, if only label images are needed (e.g. for transcription purposes, either by humans or through machine vision), or lower resolution specimen images are sufficient, then the current herbarium digitisation conveyor systems may be adapted for objects such as open boxes of bones, molluscs and other dry material. There may also be scope to image labels on jars

[6] http://www.bioshare.com/ and http://digitarium.fi/
[7] https://picturae.com/en/digitizing#herbarium

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from liquid collections, although this may come with increased risks to manage, if using electronics in proximity to liquids, especially flammable liquids.

Another important aspect of these workflows is that image correction, such as cropping, straightening and colour calibration, can be done automatically because there are a number variables such as shape, camera position and settings which are fixed in this workflow and type of collection.

In general, conveyor belts can be an efficiency boosting component when certain conditions are met. First, it takes a certain amount of time, effort and space to set up a system with a conveyor belt. The quantity of material needs to be large enough to balance the set up time/cost. Secondly, the diversity of the material needs to be within a set range. For example, this includes dimensions, views to be captured, acceptable levels of vibration and similar parameters. Further, the handling needs to be able to be broken up into independent actions at certain stations of the workflow. By simplifying the handling into separate repetitive actions (and reducing the number of actions where possible) the speed of the whole process can be improved. Finally, all the necessary preparations to standardise and prepare the collection for automated digitisation need to match the speed of the conveyor belt. This is the key barrier to optimising the benefits of automation through these systems. The experience of many digitisation projects (in both cultural heritage and natural history) shows that the amount of preparation work and the impact on the collections department is often underestimated. This is especially relevant for digitisation projects procuring a conveyor belt system and/or service through outsourcing, where it is not economic to stop and start the process.

Case study 2: Automation of 3D imaging – CultLab3D

The Competence Center Cultural Heritage Digitization of Fraunhofer IGD[8] (Darmstadt, Germany) has developed multiple mass-digitisation 3D scanning solutions for cultural heritage that can be used for industry and natural history without issue (Santos et al 2017ab, Ritz et al 2018). More specifically, industry examples include 3D scanning shoes for e-commerce; while cultural examples include globe digitisation at Friedrich Schiller University. Fraunhofer IGD is a German research institute focussing on various fields in applied science. That it has been developed specifically for heritage is rare and a great advantage. The developers understand the limitations of working with heritage objects and the need of curators for high quality and calibrated, repeatable results. For this case study various conversations were held with Pedro Santos, head of the competence center, and an open day with demonstrations & discussion session was attended at the Getty Research Institute in Los Angeles (USA) on 15/07/2019. This visit was part of the alternative plan for the second WP3 roundtable. The full report is available in Appendix 1.

[8] https://www.cultlab3d.de

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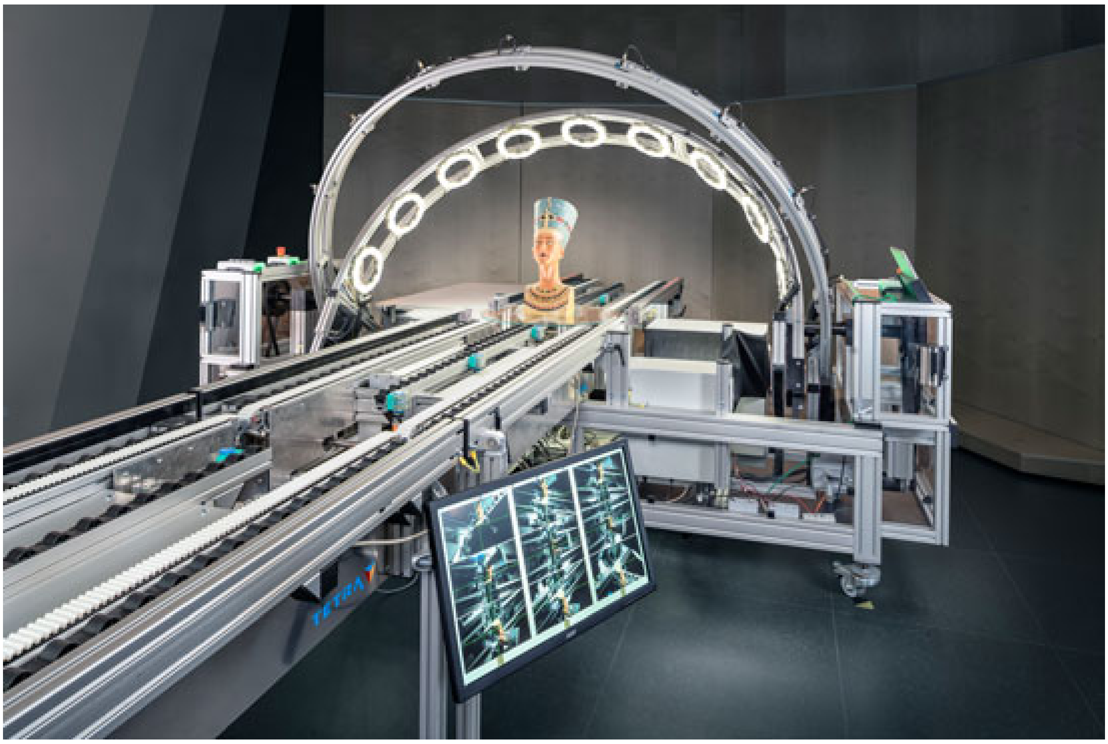
Their first solution is named CultLab3D (see image below): a conveyor belt system equipped with cameras on two half-arcs with ring lights and glass turntables to allow imaging of the object's underside. Multiple objects can be loaded onto the conveyor belt, so that the imaging system doesn't have downtime while a human operator loads the next object.



CultLab3D in action, showing the double arcs and conveyor belt. Source: https://www.cultlab3d.de/index.php/cultarc3d/

The newer solutions, named CultArm3D (see image below), are mounted on robot arms and can be either photogrammetry, laser or structured light based. This allows flexibility in choosing the right solution based on cost, resolution, object surface type and colour accuracy requirements. The system can work with standard DSLR cameras, as well as professional high-resolution Phase One cameras. With the current camera and lens combination, objects with dimensions between 40*40*60cm (max 20kg) can be digitised, and with a maximum resolution of 20 microns. When different lenses and a robot arm with longer reach can be used, smaller and larger objects can be captured. Highly controlled focus stacking for small objects is an option. These robot arm systems can also be attached to the end of the conveyor belt system when insufficient data is detected in specific areas after initial alignment, to target these areas only.

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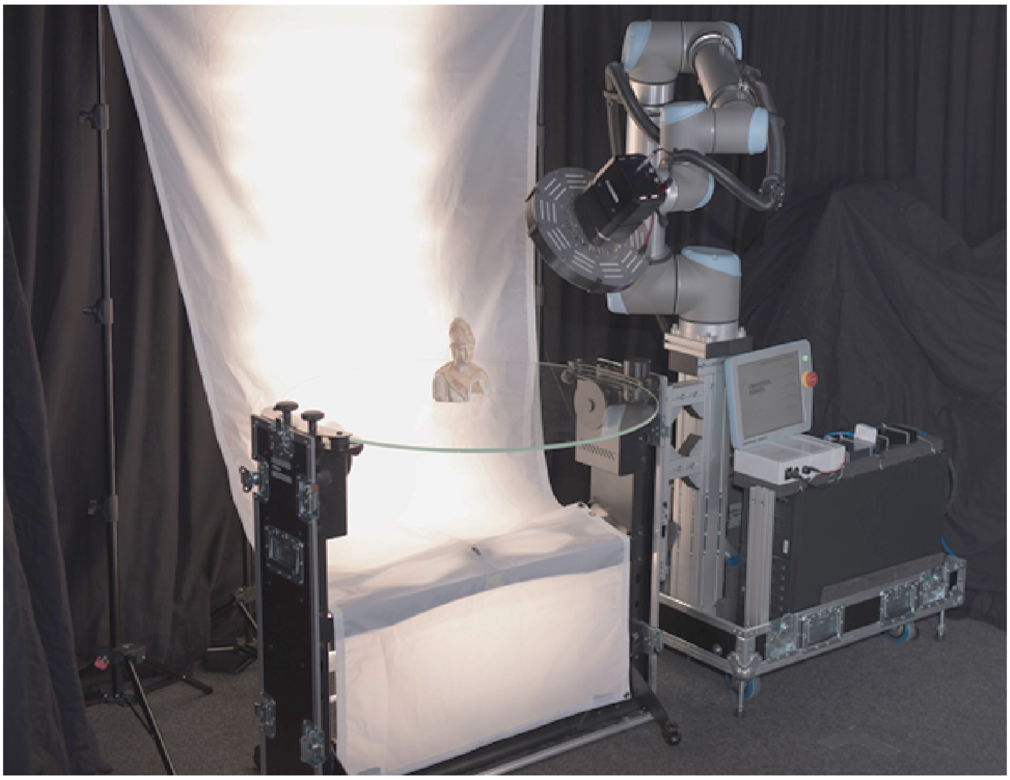

“Portable” CultArm3D setup with glass turntable and backlight. (Source: CultLab3D Fraunhofer)

The CultArm3D system is fitted with a glass turntable (manufacturer: PhotoRobot) so that the underside of many objects can be sufficiently captured. Two positions have been pre-programmed to minimise refraction from the glass as well as ensure that the arm does not hit the turntable. This does mean that objects with complex undersides (or objects with no definable undersides, which includes many non-man made objects) will still need to be repositioned to properly capture them from all sides. Another scenario are objects that will not sit sufficiently stable by themselves so that they require some support. As long as there is sufficient contrast between the supporting material and the object, it can be removed automatically.

The capturing system is not compatible with Mac. The computer specifications for capture are very low: it can run on a lightweight laptop. However, the requirements for the processing stage are a bottleneck. A typical capture results in hundreds of images.

The safety of the object and of humans in the vicinity needs to be assured to make this robotic system viable. To do this, multiple layers of security measures are present. The robotic arm (Universal Robotics UR10) is designed to be safe for human workers in its vicinity. Due to its inbuilt collision detection, such as during contact with a human, the arm will freeze. The same happens during a power failure, where some other robotic arms might unlock their joints so that gravity pulls the components down. The arm is programmed with predefined zones where it is not allowed to come, this includes the turntable and some other areas. Finally, based on an initial scan, a cylindrical space is defined that the arm cannot enter, giving a safe margin around the object.

Fraunhofer IGD has optimised their solutions to a great extent while keeping it adaptable. After calibration and besides loading objects, the capturing process does not need a human operator. The object is initially photographed against a lit background so that only the silhouette is captured, which some software can use to improve photogrammetric algorithms. The robot arm is an off-the-shelf product which Fraunhofer can upgrade at a later point, including on existing systems. While Fraunhofer's code should work with a new model robotic arm made by the same manufacturer from the same product line, only minimal code changes would be needed for a different arm, as long as it has the same degrees of freedom. Focus stacking processing, and detection and discarding of unsharp areas in the photos are done through scripts. To optimise the quality of the output, their pipeline generates depth maps to be able to ignore poor data (out of focus) in the images. The processing pipeline is not locked to a specific photogrammetric software, and can use either various commercial packages, open source software or software developed by Fraunhofer, as long as it is scriptable. Fraunhofer has developed software to optimise the 3D output for various presentation goals including web optimisation (this includes UV unwrapping, retopology, normal maps, publication in web specific format).

Fraunhofer's 3D scanning robot has been designed to fully automate the capturing process, as well as capturing extra data to be able to fully automate the 3D processing workflow. Some human interaction may still be required during post-processing, especially for the more complex objects. Compared to the herbarium imaging solution, the system deals with added complexity because of the 3D nature of the objects and many more processing steps that the raw captures and generated models need to go through.

Fraunhofer's solutions are advanced in optimisation and automation, but the adoption by collections is limited due to cost and floor space requirements of the original CultLab3D conveyor system. In some instances also, technologies like these can be a rather 'gold plated' solution for natural history collections rather than cultural objects - they are perhaps more suited to outstanding objects or particular object types than to typical 'mass' digitisation of thousands of natural history specimens. The components, both hardware and photography/photogrammetry software, are off the shelf solutions, so Fraunhofer's goal is to make use of the development of more affordable options. These solutions are informative for ICEDIG's automation recommendations because of the flexibility of components, while also being fully integrated. The original system used a conveyor belt to minimise downtime during loading, but they have found that this solution could potentially be obsolete due to the ease of loading objects and space requirements.

Case study 3: Robot arm for exhibitions

As described, one of the limiting factors in automated specimen handling is the absence of proven solutions to pick up natural history objects and place them in a specific way in a specific place, without damage. Because most existing solutions are targeted at fields of industry dealing with very different factors than found in NH collections, any development in a related field is of interest. The Robocase[9] developed by exhibition designer Bruns, in collaboration with software maker Kiss the Frog[10] (both from the Netherlands), is of interest for this reason[11]. It is designed specifically for handling museum objects on a standardised base 'plate', for display. The robot arm sits on rails that can move in two axes, and the arm itself has multiple degrees of freedom. The robot arm takes an object on a base from a shelf or drawer in a specifically designed cabinet, then transports the object to the viewer, usually placing the object on a turntable so that it can be viewed from all angles. This displaying behaviour depends on the object and the computer code behind it. The idea is that a visitor can use a screen to choose an item to view up close, then the robot retrieves, displays and returns the object. It is possible to have multiple robot arms in one Robocase. The whole process has been designed with reliability and safety of the objects in mind.

To achieve this innovation, Bruns undertook extensive research on robot arms for museum objects. Initially, their idea was to develop a system that could handle the objects directly. The robot arm had to be able to work in slow and steady movements with high repeatability. Also, for this purpose a range of grippers were investigated and tested. Due to the variety of objects and the desire to also interact with cabinet doors and drawers, it proved too hard to find a reliable flexible gripper for handling the objects directly. Instead, a design was made of a hook end effector, combined with low pedestals on which the objects were placed. These pedestals / bases have a slot in the side, which the hook slides into so that the pedestal with object can be moved. This hook was also designed to be able to interact with the cabinet doors and drawers.

This means that this robot arm does not directly handle the object. Also, the system does not have sensors to locate and precisely pick up objects, this is done by storing the location programmatically. For natural history collections the lesson here is that it is easier to get a robot to interact with standardised containers, than it is to develop a system that can handle a wide range of specimens.

[9] https://www.bruns.nl/nl/nieuws/robocase-duikt-voor-de-museumbezoeker-de-kast-in
https://bruns.nl/en/news/robocase-nominated-for-the-heritage-in-motion-award-2018
[10] https://www.kissthefrog.nl/portfolio/robocase/
[11] For this section, and interview was held with Patrick Vermeire of Bruns on 13-09-2018.

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Bruns RoboCase retrieving an object on a low pedestal. (Source: Bruns)

Case study 4: Automated Warehousing at the British Library

Besides automation in relation to digitisation, automated solutions similar to those used in commercial warehousing can be used for the large-scale handling and retrieval of natural history objects in storage, improving retrieval times from storage, space efficiency, and allowing for e.g. low-oxygen environments which are beneficial for conservation of some collections but can be dangerous to humans. Library collections are close to natural history collections: they serve to make object based research available; most of the objects spend most of their lifetime in storage but need to be retrievable in ways that are often not predictable; and object condition depends on controlled climate (temperature, humidity, oxygen levels, and pest control). Library books have somewhat fewer variables than natural history collections do, although similarly for automation they rely on standardised storage, with e.g. books in crates, boxes or 'bins'; and newspapers or other larger formats secured on pallets.

In recent years, some large libraries, on a national level or at large universities, are building advanced warehouses with storage robots. Some examples are the Glucksman

Library at the University of Limerick[12], Macquarie University Library[13], North Carolina State University Library, University of Missouri Kansas City Library[14] and University of Chicago Library[15]; these systems are developed by Dematic[16]. In most cases, the books are stored in standardised steel bins, which the robot can manipulate and take out in full when a book request is made through the catalogue. The physical storage location of the book is recorded in the database. The organisation of the objects can remain as it was before (e.g. by topic, author, year, language) but this is not necessary. (In the event of complete database malfunction with no backup data available all books would be untraceable, but with a backup protocol in place this should never occur.) After the request is made, the robot retrieves the bin in which the item is located. The whole bin is then made accessible to a librarian, who takes out the specific requested item and processes it for pick up by the requester. The rest of the bin is returned to storage. Return is very much the same: either a random bin or the dedicated bin is retrieved by the robot for the librarian to put the book into, after which the bin is automatically reshelved.

Usually the parts of the collections with highest use are still available on the shelf for the readers and only the “reserve collections” or less used collections are in the automated warehouse.

The British Library started with a project for a new building and automated storage system in 2004-2006[17]. A second building and automated storage system with shelves going 30m high went live in 2015 for the newspaper collection[18]. The company that built the systems for them is TGW Group. After trial and error, they discovered that bundling and securing a set of newspapers with a canvas belt was the simplest solution for librarian and robot. In the first automated warehouse there initially were problems with the size of the boxes (up to 2m), distortion of the boxes and misalignment of the cranes with the isles; these issues have now been resolved.

The items can only be accessed and requested through the systems. A user, e.g. in the reading room in London, can request an item through the digital catalogue. The request is then sent to the system in Boston Spa (Yorkshire, 280km north of London). The robot retrieves the bundle for a librarian to take out the specific requested item. The rest of the bundle is returned by the robot to its place, while the requested item is set aside. Once a day all requests are gathered, sent by courier to the reading room in London where the user has access. After use it is sent back by the same route; the whole outgoing process can be done within 24 hours after the request is made.

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[12] https://youtu.be/bd9-0QVnNTU
[13] https://youtu.be/5SegEbE_QhM and https://youtu.be/GuLlvR89djM
[14] https://youtu.be/8wJJLlTq7ts
[15] https://youtu.be/ESCxYchCaWI
[16] http://www.dematic.com; http://www.automatedlibrarysystems.com/
[17] For this section, an interview was held with Andy Appleyard (Head of Operations (North), British Library) on 01/10/2018. He also was an invited contributor to the first WP3 roundtable, held on 10/12/2018 at Natural History Museum, London.
[18] https://youtu.be/AY6B0wNisUY and https://youtu.be/j8Ptzt_Gfw4 and https://www.tgw-group.com/en/news-press/press-releases/tgw-in-partnership-with-the-british-library

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While the system is not accessible to humans, they have maintained their original systematic organisation by subject and author. Maintenance of the hardware is not done by library staff: like cleaning services, it is completely outsourced to specialised engineers on call. Support is reduced out of hours (e.g. overnight) owing to cost - systems are still used at these times but the functions used are reduced to those where the BL operators can usually resolve any issues themselves. The newspaper warehouses contain 70km of storage. To make this work every item needs to have its own identifier and physical storage needs to be completely in sync with the database and software; this initially proved to be a challenge. Over the years, no objects have been dropped, however there have been a few cases of objects or bins becoming stuck. After the initial phase, they now experience very little issues. With the number of overdue outstanding request as indicator, there are almost never problems.

The workflow of the users has changed very little because these items were only available on request already, with 24 hour processing time. The work of the librarians has changed: to keep up with the demand they work in shifts and due to automation the work can be done with less training. The newspaper collections were not in the best condition before the move to the new automated warehouse; now their condition is stable. Because the storage area is off-limits to humans, a much lower oxygen and temperature level can be maintained (oxygen comparable to Mount Everest) which is the main source of deterioration of the material. The low oxygen level also reduces the risk of fire. Another major factor is cost: in London the cost of a meter of shelving space was about 40GBP, in Boston Spa that is 4GBP. This is also due to the use of automation to enable storage at a much greater height than would be usable by humans without assistive technologies.

Advantages of this solution are space efficiency, lower housing cost from off-site storage, improved specimen conditions due to climate control, and reduced fire hazards. A major part of the current workflow of natural history curators and researchers is to browse the collections, going through boxes and shelves, enabling associative specimen selection. This can be a specimen sitting next to the initial target, from the same location, same collector, same label format etc. An automated warehouse would not allow this workflow physically. However, this can be achieved through software solutions. Imaging per shelf can substitute initial shelf/box browsing; image recognition of labels, transcribed metadata such as collector and location would make the other approaches even queryable. A tiled view with associated material of the specific request based on taxonomy, location, collector would also recreate this workflow.

Most current library warehousing robots still require human picking from bins. This offers a useful lesson for natural history collections in relation to standardising storage units where possible - while the variety of items and storage types is greater than in libraries, the volume of many collections could still allow for extensive standardisation of e.g. drawer or jar size, shape and other features. The key benefits of automation at scale for specimen handling involve the complete refitting or new development of storage spaces, so can only be considered e.g. when moving collections at scale to new or refurbished facilities, however pilots such as the use of a small robot to fetch collections of one type within one storage area may be possible. There is a potential to collaborate with other collection-based institutes: either other natural history museums in the larger region, cultural history collections (museums, archaeological departments) and libraries. This would reduce the cost of building new facilities and the transportation to the main site.

Case study 5: E-commerce warehousing solutions

Robots and automation are being rapidly adopted and developed for e-commerce logistics and order picking. Companies such as DHL, Amazon, large grocery stores (Ocado in UK) are adapting their warehousing process to extensive automation. The process known as order (or item) picking is closest to the needs of natural history collections.

One variant is where the entire cabinet/shelving system containing the requested object is picked up by a transporter robot, and transported to a human for actual object picking[19]. For example, this is used by Amazon (developed by Amazon Robotics, formerly Kiva Systems [20]). An alternative is a grid system with crates or racks of goods below and autonomous robots on top, navigating the grid to pick up an object or packet using a suction cup, storing the item in the cart and dropping several objects at a packing station for further shipping, as used by Ocado and produced by Swisslog[21][22]. “Each of the bots has a central cavity and a set of claws it uses to grab crates and pull them up into its interior, like an alien abduction in a supermarket aisle. It can then move the crate to a new location or drop it down a vertical chute to a picking station. At these stations, human employees grab the items they need from the crate (a screen in front of them tells them what to take) and places them in a shopping bag in another crate. Both these crates are then sent back into the grid, to be refilled with shopping items or moved on to the delivery bay.”[23]

These examples demonstrate the massive scale at which roboticised warehousing operates and how humans are still needed for object handling tasks. Amazon does not expect to have robots working end-to-end within 10 years[24]. One of the benefits that these examples have, which natural history collections don’t, is the ease of replacing a requested object if it gets damaged or lost - a degree of cost for such damage is factored into the

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[19] https://youtu.be/UtBa9yVZBJM (Accessed 25-09-2019)

[20] https://en.wikipedia.org/wiki/Amazon_Robotics (Accessed 25-09-2019)

[21] https://youtu.be/4DKrcpa8Z_E (Accessed 25-09-2019)

[22] https://www.swisslog.com/en-au/newsroom/news/2018/07/swisslog-delivers-a-second-autostore-installation-for-ocado (Accessed 25-09-2019)

[23] Source: https://www.theverge.com/2018/5/8/17331250/automated-warehouses-jobs-ocado-andover-amazon (Accessed 25-09-2019)

[24] https://www.theverge.com/2019/5/1/18526092/amazon-warehouse-robotics-automation-ai-10-years-away (Accessed 25-09-2019)

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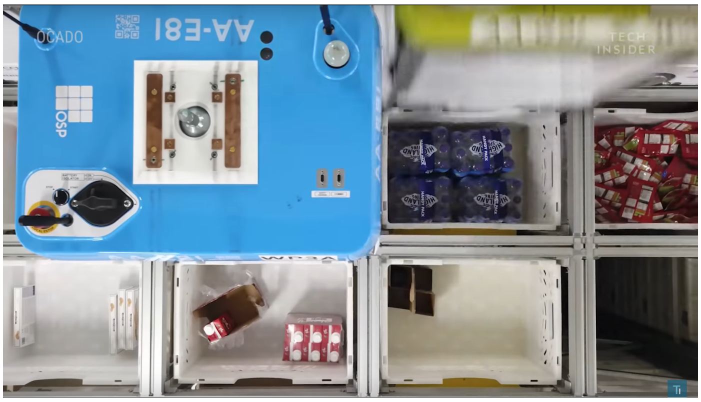
business case for these solutions and is acceptable to these companies in the light of the overall cost savings.

It is worth noting that a report by DHL in 2016, examining the potential for robotics and automation in logistics, raised concerns that any 'logistics robot would need to handle a wide array of different parts in an infinite number of combinations. It would help if the robot could see, move, and react to its environment.'[25] This echoes some of the barriers we believe may exist in our sector and mention in this report - however automation is now increasingly widespread and vital to the logistics industry so this is a useful lesson in how quickly limitations are being overcome.

https://youtu.be/UtBa9yVZBJM 0:08



https://youtu.be/4DKrcpa8Z_E 1:16

https://youtu.be/4DKrcpa8Z_E 1:42

Case Study 6: Remote microscopy

In 2012, Wheeler et al proposed the use of remotely operable microscopy to engage taxon experts in targeting and annotating information about type specimens, as part of a 4-step

25 https://www.dhl.com/content/dam/downloads/g0/about_us/logistics_insights/dhl_trendreport_robotics.pdf

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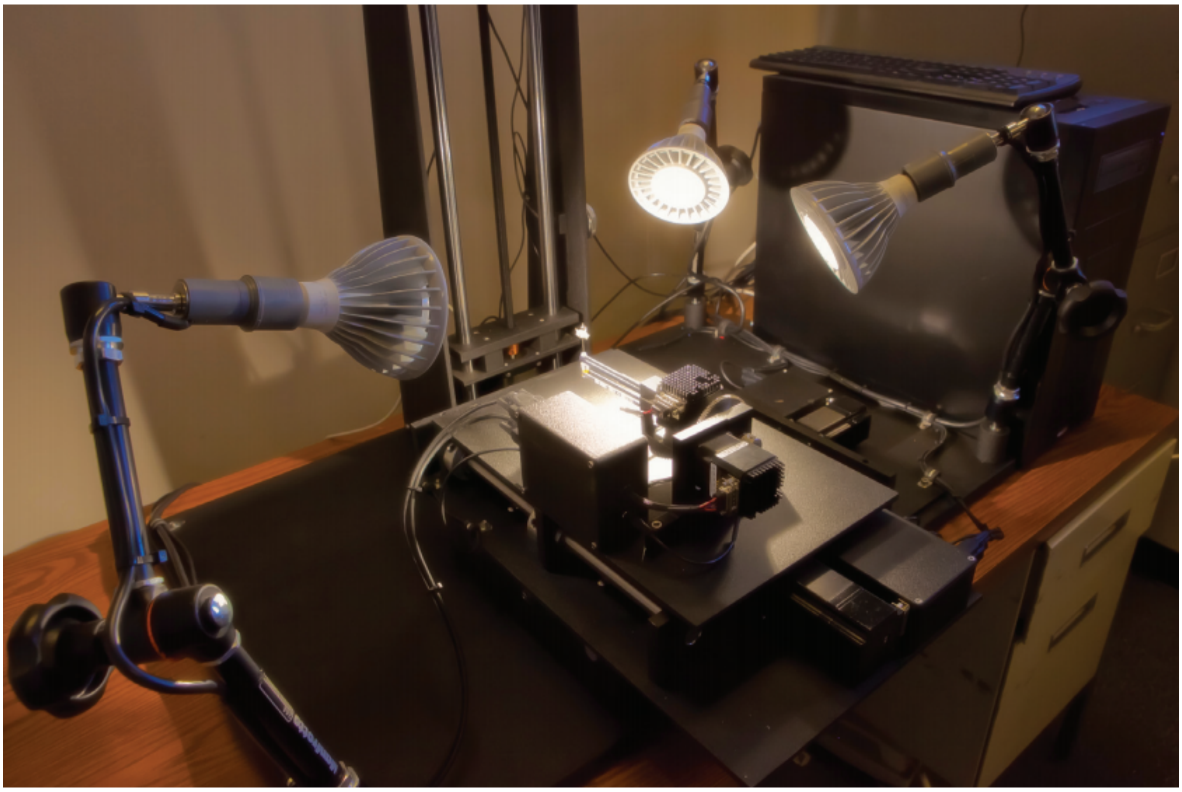
approach to improving nomenclatural benchmarking. This approach built on ‘telemedicine’ or ‘telepathology’[26] practice, which uses technology to facilitate remote sample examination and diagnosis using either digitised images of e.g. microscope preparations; or cameras, including mobile phone cameras, attached to microscopes to transmit images over the internet.

For this initiative, a system was developed known as ROBOT(E) (Remotely Operable Benchmarker Of Types, first used in Entomology). ROBOT(E) was designed to allow taxonomists to examine, manipulate, and digitally photograph type specimens through a Web connection. Three such instruments were set up in the major insect collections in Washington, London, and Paris. The goal was to minimise costs and maximise reliability and simplicity by using as much off-the-shelf technology as feasible, including a Canon 7D camera that allowed auto-focus and through-the-sensor high resolution viewing. The specimen holder was designed to allow pinned specimens, held in a tight bundle of fine acrylic cable, to be rotated 360 degrees and ‘rolled’ 180 degrees to reveal the ventral surface. Software was written to control the ROBOT(E) using mouse, arrow and button commands to move the system’s motors and e.g. control focusing. Images were stored in a temporary folder from which they could be downloaded to any target folder.



The ROBOT(E) remotely operable digital imaging system. PHOTO:Erik Holsinger, Arizona State University (Wheeler et al, 2012)

[26] https://en.wikipedia.org/wiki/Telepathology

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This system appears not to have been well-used in practice when the pilot was deployed. The authors noted that 'This is not a general solution to type accessibility or a substitute for creating e-types. We propose a broader strategy of which this direct connection of expert and type is merely one component.' - in practice, digitisation in 2D or 3D is often the best method to satisfy the needs of remote access to specimens and their data, provided sufficient views are taken to satisfy diagnostic and research uses in most cases. Remote solutions require collaboration between human operators at both 'ends', e.g. to place material into the system, but the nature of tasks as each end may not align readily e.g. processes are needed to alert an operator that the remote examination is complete, and this timing may not fit well with other tasks they are performing. A strong internet connection is of course also required for remote examination - this may now be more readily available in more locations but is not universal. Overall, it seems likely that technological solutions for remote specimen examination are more likely to be useful in research and collaboration involving small numbers of specimens, or with a time-critical driver such as medical diagnosis, than in the mass handling or digitisation of collections where digitisation can usually provide high quality remote access in a repeatable, low-cost way.

Case Study 7: Robotic handling of liquid vials

The Molecular Collections facility (MCf) at NHM London has a Hamilton Microlab Star Robotic Liquid Handling Workstation, which was purchased and installed in 2011 to function as part of the NHM's molecular pipeline.

The robot is located in MCf's Preparation Room and performs pre-PCR (polymerase chain reaction) sample bulk analysis and processing (sample reformatting, quality control/assurance, DNA/RNA extractions and PCR reagent set up) prior to post-PCR processing (PCR, next gen sequencing) on its 'sister'/same model Microstar robot next door in the NHM's Sequencing Facility. Workflow formats, consumables, scripts, service and maintenance contracts, including technical and apps support, are shared between the two robots for cost efficient high throughput molecular pipeline sample processing and workflow development.

MCf's robot was first used in 2011 - 2012 to reformat and assess the quality of legacy molecular collections, e.g. transferring DNAs in solution into 2D barcoded cryo-vials for modern biobanking in the NHM's new cryofacility (-80 ultracold and -196 degrees Celsius LN2 freezers). Since 2012 the robot has been used by Sequencing Facility staff in CRL, mainly for bulk DNA extractions, automating researchers' preferred DNA extraction kit methods e.g. Qiagen's DNeasy kit. Additional robotic workstation deck accessories have been purchased since the robot's original installation, including integrated automatic 2D/1D cryo-vial and rack barcode readers, magnetic bead and vacuum extraction units. Further accessories can

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be added as required, plus 3rd party equipment integration, with interchangeable deck set up for flexibility and future proofing.

The following technical information from the suppliers (Hamilton) describes the robotic workstation specifications in detail: **MICROLAB® STAR Liquid Handling Workstatio**n: The STAR line workstation is based on superior air displacement pipetting technology. This increases accuracy and repeatability while providing chain of custody with pipette condition monitoring and recording. Each workstation can be configured with multiple arms and each arm can be configured with multiple pipetting and labware gripping devices. Pipetting channels and labware grippers move independently of each other, supporting the use of a wide range of labware. The autoload option provides barcode tracking of samples, labware, racks and carriers. All workstation functions and integrated third-party devices are controlled by the Venus software. Data can be tracked and processed within the application as well as interfaces to internal and external databases, including LIMS. The STAR can serve as a simple pipettor for serial dilutions or act as the center of a large system with multiple workstations and third party devices such incubators, cell counters, centrifuges, etc.
From https://www.hamiltoncompany.com/automated-liquid-handling/platforms/microlab-star

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Specifications for R&D: discussion

One of the goals of this task as set out by ICEDIG is to produce sets of specifications for research & development, specifically aimed at SMEs. To achieve this, various businesses in the relevant industry sectors were approached, as well as technical universities and their spin-off companies. Unfortunately, very little response was received. This in itself is valuable and an opportunity to learn.

In total more than 50 people in various functions and at various institutes were contacted. They were initially selected for their experience in the field of robotics which could line up with the needs of natural history collections. The tasks of digitisation, handling and warehousing were the main focus of this selection. For example, some of the companies approached had experience in automated handling of fragile, organically-shaped objects in the agricultural sector (eggs, flowers, live chicks). Among companies approached were both users and developers, with the intent to gain diverse feedback. A lot of the approached contacts, by phone and email or contact forms, either did not reply or did not identify the correct person to respond. For example, a specialist robotics department of a technical university, linking research and industry, was contacted for collaboration but contact with an expert could not be established.

The engineer that Picturae worked with during the development of the herbarium conveyor belt was one of the few who was available for extended contact. He indicated that during the development of the herbarium conveyor belt there was a clear requirement of safe transport and automated recognition of the specimens. For any new roboticised developments there is a need by SMEs for similar clear specifications. Industry can't be expected to come up with solutions for problems that are specific for natural (and cultural) history collections. Only through clear requests, and demarcated problems that need to be solved, can industry attempt to contribute. One of the issues is that the term 'biodiversity collections' or similar is largely unknown to this sector.

A previous example during which natural history collections similarly failed to gain sufficient engagement from technologists was the Beyond the Box competition, by the American Institute of Biological Sciences and the National Science Foundation (2014-2015)[27]. This offered an award of $1 million (USD) to the person or team who created a technology that increased the speed and accuracy of digitization of a drawer of insect specimens and their associated data. After the deadline, no submissions were received which met the requirements, resulting in no award made. While this competition was backed with a large sum of prize money to attract competitors, this fund was specifically to further develop and to market the solution, putting off some not-for-profit entrants, and in addition the rules and

[27] Accessed on 19/09/2019 through https://web.archive.org/web/20150706195815/https://beyondthebox.aibs.org/ (before competition deadline) and https://web.archive.org/web/20160323003004/https://beyondthebox.aibs.org/ (after competition deadline)

interaction were strict which may have affected the outcome. When seeking technical collaborators it is important to allow means for them to become familiar with the requirements and limitations of specific natural history collections. This competition laid out various rules, with strict levels of achievement and a set of abstracted test material (PDF, with dimension and location details of drawers, unit trays and specimens); giving a limited range of flexibility for the potential contestants. Because roboticised solutions for most heritage collections are high in complexity, more interaction is needed to establish a suitable solution. In any future competition, a better outcome may be achieved by defining the outcome, rather than the approach. It may be helpful to consider examples of competitions in other sectors, such as the Amazon Picking Challenge[28].

Many SMEs in the automation industry have a large enough market in various sectors (manufacture, logistics, food production). In comparison, the natural history and heritage sector is small and complex, as there are various sub-collections that require their own treatment. Developers need an incentive to focus on the heritage collection market, which often translates into making funds available for development. Funds available for selling or service provision are often not guaranteed and allocation of these funds depends on procurement laws.

During the research for this report, no concrete new developments were found that are (nearly) ready to use in natural history collections. If there is a desire to use automation solutions in natural history collections for warehousing or digitisation, then some steps are needed on the part of the NH community. We propose that a series of pilot projects is established, which SMEs can participate in. This could take the form of innovation competitions with multiple phases, or partnering between specific institutions to solve R&D challenges, perhaps bidding into relevant government or similar innovation funding. These approaches will usually allow greater interaction between industry and collection holders, and greater exploration and flexibility around requirements, than a standard procurement. The various pilots in the series could be targeted at the various collection and preservation types, ideally across multiple collections-holding organisations. DiSSCo could play an important role in this. By doing this series of pilot projects, both industry and collection holders learn from the process, working towards increased efficiency with specialised automated solutions.

DiSSCo, and its Centers of Excellence, could play a further role in developing the expertise to better communicate with SMEs, supporting institutes when they want to approach SMEs for specific topics. Part of this is experience with demarcating the problem, setting functional requirements and being able to discuss desirable outcomes. Automation SMEs from outside the heritage field are unlikely to know how fragile and variable the material is; what can and can't be done during handling; the importance of labels and systematic collection structures; which views of the specimen are important, etc. A DiSSCo Center of Excellence could assist with the process of making specifications and requirements

[28] https://arxiv.org/pdf/1601.05484.pdf

clear. Also, DiSSCo can lead a concentrated effort for research and development in this field, to make sure that the various pilot projects are aligned.

Conclusion and next steps

For this report the current state of robotics and automated warehousing was investigated in relation to the storage, handling and digitisation of natural history collections. Several examples of automation from e-commerce and the library sector were explored. Two examples of a robotic arm in the heritage sector were also studied.

Robots and other automated systems are very good at repetitive tasks. Natural history collections are a challenge for robots because there is very little that is standardised between natural history collections, within those institutes and even within one type of collection.

At this time, a fully automated solution from storage to imaging and back to storage is not realistic for the complex context of natural history collections. By developing independent components which can be connected in the future, progress can already be made towards an end-to-end solution. For the imaging component, due to the great variety of natural history collections it is inevitable that multiple automated imaging systems are needed.

Looking at the microsteps required during hardware - object interaction, it becomes obvious that the current state of the art is not yet ready for the objects of natural history collections. Automated handling of specimens for digitisation and other purposes depends on several components: robot arms, grippers, sensors, computer vision and software. There are several options that can be considered, for several components. The first option is a robot for warehousing tasks, that is able to operate the existing shelving units and drawers. The second option is an alternative for the warehousing task; the existing storage units can be replaced with special units designed for robot interaction. The third option is for individual object handling: a robot which can handle individual objects (at smaller storage unit or specimen level). An alternative for automated digitisation is the use of robot arms with attached camera, circumventing the need for the robot arm to interact directly with the specimen. The cost, precision, reliability and ease of implementation of these components will determine the success of automated handling of specimens. The goal to make Europe's natural history collection digitally accessible can only be achieved by increasing the efficiency of digitisation, and part of this is through software automation.

The investigated case studies cover examples of solutions for components identified for end-to-end automation in natural history collections for collection management and digitisation. Herbarium collections provide the best examples of automated mass digitisation as there are currently two of these solutions (by Digitarium[29] and Picturae[30]). These systems

[29] http://www.bioshare.com/ and http://digitarium.fi/
[30] https://picturae.com/en/digitizing#herbarium

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still require handling by human operators to load and unload, to apply barcodes, and to detect special specimens such as types and specimens requiring restoration. The conveyor belt component of these solutions may be used to automate digitisation workflows of other collections. If only the labels need to be imaged in high quality (for transcription purposes, either by humans or through machine vision) and the rest of the specimen needs only to be imaged for overview functions, then the current herbarium digitisation conveyor systems may be adapted easily for other collection types.

An automated 3D scanning solution developed specifically for heritage objects demonstrates the use of an automated camera solution mounted on a robot arm. Using a robot to automate the camera and its movement may be easier to achieve than handling of specimens, and may be further adapted for digitisation on demand.

Besides automation of object handling and imaging, warehousing automation can improve retrieval times from storage, space efficiency and climate control. However, implementation of automated warehousing solutions would require significant adaptations of existing storage space. This option may be of greater interest when new storage spaces are being built. One of the options implies switching to shelving units that a robot can operate.

Several components were identified for various collection management tasks that could potentially be automated. This includes storage & retrieval, transport, object picking, and imaging. An end-to-end solution is not available, so by developing these components independently with future integration in mind, progress can be made now.

The natural history sector will need to work with suppliers and subject matter experts, who have the required expertise to develop and integrate components. Natural history collections have very different requirements than the e-commerce sector, so SMEs need to be provided with clear requirements and information, as previous experiences show. Competitions and tenders will need to allow for SMEs to see collections in action and to ask questions to gather information and experience that they require for development.

If there is a real desire to use automation solutions in natural history collections for warehousing or digitisation, then some steps are needed on the part of the NH community. We propose that a series of pilot projects is established, which SMEs can participate in.

DiSSCo, and its Centers of Excellence, could play a further role in developing the expertise to better communicate with SMEs. Also, DiSSCo can lead a concentrated effort for research and development in this field, to make sure that the various pilot projects are aligned.

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Appendix 1: Report of Open House CultArm3D at Getty Research Institute

15-04-2019 Los Angeles, USA

Programme

10:00-10:30 Short statements from the Getty and Fraunhofer

10:30-12:00 Demonstration of the technology

12:00-1:00 Lunch

1:00-2:00 Exhibition tour or Getty grounds walk

2:00-4:00 Hands-on testing

4:00-5:00 Discussion and panel talk on the value and future of 3D in GLAMs

The members of the discussion panel are:

- Charles Walbridge (Minneapolis Institute of Art)
- Emily Pugh (GRI)
- Pedro Santos (Fraunhofer)
- Tassie Gniady (Indiana University)
- Thomas Flynn (Sketchfab)

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Outline

Ideally 3D capture should give consistent results in geometry and colour. Traditional handheld, and even tripod based, photogrammetry can't do this. This demonstrated system should be able to achieve this as best as is possible. With this solution, photogrammetric capture comes with a lot of variables that are either consistent or specifically optimised for each object. It elevates photogrammetric capture from subjective (even artistic) to scientific and standardised.

Another goal is to achieve a watertight mesh, but not going as far as faking data to close holes. Fraunhofer prefers software that does no interpolation: MicMac[31]. This is the real observed, scientific data. However, they use other photogrammetry software as well because they want the capturing hardware to be independent of photogrammetry software. The strictest requirement is that the photogrammetry software is command line accessible.

Final preparation for web viewing is done through their own software, currently a Fraunhofer spin-off company: RapidCompact by DGG[32], includes decimation, UV unwrapping and normal maps.

In theory the system is quite camera independent, as long as the camera can be controlled programmatically. This means it is adapted to use high resolution PhaseOne mirrorless cameras (iXG, 100 mpix), Canon and Nikon DSLRs as well as laser and structured light scanners. The benefit of the PhaseOne cameras is that the focal plane is completely reproducible which makes it possible to pre-calibrate. Through the use of the robotic arm, the exact position of the optical center is known, which almost completely removes the need for camera position calculations. This removes a significant part of the alignment calculations so that alignment can be sped up significantly and is more reliable. This also means that the scan is already scaled to real world size, in contrast to uncontrolled photogrammetric capture.

The system is currently designed to be transportable: it all fits in 4 cases, takes roughly 1 hour to set up (including calibration) and weighs approximately 300kg. During the test at Getty Institute it was moved several times, which was done quite quickly and caused no issues.

The system is fitted with a glass turntable (manufacturer: PhotoRobot[33]) so that the underside of many objects can be sufficiently captured. Two positions below the turntable have been pre-programmed to minimise refraction from the glass as well as ensure that the arm does not hit the turntable. This does mean that objects with complex undersides (or objects with no definable undersides which includes many natural history specimens) will still need to be repositioned to properly capture it from all sides. Another scenario are objects that will not sit sufficiently stable by themselves so that they require some support.

[31] https://micmac.ensg.eu
[32] https://www.dgg3d.com/
[33] https://www.photorobot.com/robots/turntable

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As long as there is sufficient contrast between the supporting material and the object, it can be removed automatically.

The capturing system is not compatible with Mac. The computer specifications for capture are very low: it can run on a lightweight laptop. However, the requirements for the processing stage are a bottleneck. A typical capture results in [600?] images.

The safety of the scanned object and of humans in the vicinity needs to be assured to make this robotic system viable. To do this, multiple layers of security measures are present. The robotic arm (Universal Robots[34] UR10) is designed to be safe for human workers in its vicinity. Due to its inbuilt collision detection, such as during contact with a human, the arm freezes. The same happens during a power failure, where some other robotic arms might unlock their joints so that gravity pulls the components down. The arm is programmed with predefined zones where it is not allowed to come, this includes the turntable and some other areas. Finally, based on an initial scan, a cylinder in which the arm can't come for this specific object is defined.

Process

Calibration is only necessary when the whole system is moved, or a change in camera, lens or turntable is made and is designed to be simple. After calibration, a human operator is only required to load and unload specimens, and to start the capturing process.

The capture is done in multiple phases (De Stefano et al 2016). The first phase is called the pre-scan, which is an initial capture of the object to determine shape and size and position, used for safety measures and planning for the next phase. The initial capture consists of the object's silhouette from a limited number of photos (e.g. 12) for a technique called space carving which uses the silhouettes to reconstruct a basic 3D volume. To obtain sharp silhouettes, a bright light behind the backdrop is used. Because the position of the camera is known through the robotic arm, size can be roughly calculated too.

The second phase is called next best view planning: based on the basic volumetric model from the pre-scan the best layout of photos is planned and captured. This includes planning to optimise capture around complex structures and occlusions and with regard for depth of field. These photos are the input data for the photogrammetric reconstruction. Also, depth maps are generated before each capture which will be used to make sure that every reachable part of the surface is covered by a minimum of 3 sharp photos.

In the future, a third phase may be added to capture even higher detail images of certain areas, or around occlusions not detectable in the first phase.

Fraunhofer is a research institute and does not intend to manufacture sets for commercial purposes, nor to lease scanners out or offer project based scanning services, on the long term.

Because the camera coordinates are known, the captured masks and depth maps, processing is designed to become fully automated.

[34] https://www.universal-robots.com/

Future developments

While the current versions are functional, Fraunhofer is still working on improving various aspects and development of additional functionality. For example they hope to use a turntable of their own design (greatly improved weight capacity), make the robotic arm height adjustable to make a larger object size range possible (1,5*1,5*2,5m), and the ring light needs to be CE certified before commercial production can really start.

Essential to any 3D capturing project is a plan for presenting the models. This is often done online. Downloadable data is a potential solution, but often download speeds are restricting the accessibility of the full resolution data, as well as local computing power. Fraunhofer is also looking into this aspect by developing an online viewer that allows private hosting. A major aspect of their online viewer is annotation on the 3D model. This maximises the potential of simultaneous and collaborative study of a single object. Another solution that they are researching is “geometric similarity measurement and retrieval”; query a database of models based on shape, independent of metadata or 3D resolution (Tausch et al 2016).

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Appendix 2: Using a risk-based approach to consider the benefits of robotics and automated warehousing in natural history collections

Summary and discussion

As part of assessing the potential for robotics, automated warehousing technologies and assistive technologies in relation to storing, handling and digitising natural history collections, we investigated key categories of risk in the Natural History Museum, London's (NHM) risk management system. This summary captures the discussion, findings and suggestions for how these could be applied. The remainder of the paper is a methodological account of the system review.

Across discussion with the Health and Safety team, and analysis of relevant risk categories and risk assessments, key risk areas fell under the broad categories of manual handling; broader environmental factors; and working alone. There is scope for automation to mitigate risks across these areas, although there are also some risk categories where the risk to robots is equivalent to or higher in severity than the risk to humans. In all cases, the usefulness of automation to mitigate risks depends on the desired outcomes (e.g. acceptable risk level) and on cost-benefit analysis relevant to the particular circumstances.

Manual handling

It is clear that there are many unavoidable manual handling tasks and risks in working with collections, some of which are occasional e.g. only incurred during major moves, and some which recur regularly e.g. producing items on request for visitors/researchers.

Annex 1 shows an extract of the manual handling risk assessment template. Review of particular risk assessments confirms the importance of the categories within this template, which cover the nature of the physical **task** required (e.g. bending, stretching, repetition); the **environment** in which the task is carried out (e.g. lighting, obstacles); the **load** (weight, bulk; hazards such as sharp edges); and the **capability** of the operator (e.g. restricted movement or conditions such as pregnancy).

Across all of these elements, mitigation currently includes a range of equipment, from personal protective equipment (PPE - e.g. gloves, masks) to other hardware such as trucks or ladders. There is scope for automation to reduce any of these categories of risk - as set out in the main report above, robots are excellent at repetitive tasks (which risk human injury); and robots or assistive technologies such as exosuits can increase the capability of humans or offer alternative capabilities e.g. in managing heavy loads. In relation to environment, specific to manual handling, robots are likely to have different requirements from their environment than humans, however their need for consistency/standardisation is likely to make risks such as access obstacles or uneven floors as much or more of a problem for robots as for humans.

Broader environment

Risk assessments and discussions with the NHM H&S team identify a range of environmental considerations beyond manual handling, where automation may help to address risk. These include **security** considerations e.g. where there is a need to limit human access to high value materials; **pest control,** where again more human movement and access increases risks to collections; factors such as **air quality, temperature and noise**, whether deliberate as in a low-oxygen or cold store, or unplanned; and **hazards** such as biological and chemical hazards, sharps; very high or low working etc.

Clearly where human access is a key element of risk, there may be scope for automated solutions - although the need for human operators to work with/on robots in many cases may reduce these benefits.

Similarly, robots may have a greater tolerance to certain environmental conditions than humans - they are unlikely to be impacted by noise, and can operate in planned environments that are not suitable for prolonged human access, such as those with low temperatures, reduced humidity or low oxygen. Again, consideration must be given to the need for humans to work with the robots and to maintain them.

In some instances, robots may have better tolerance to hazards, however there are many hazards which will pose an equivalent or greater risk to robots compared to humans, for example electrical faults, fire, leaks and corrosive materials.

Working alone

Where robots can operate without (or with minimal or remote) supervision, they may reduce the instance of collections staff having to work alone or in isolation. In general terms, it seems likely also that technologies such as environmental sensing and remote communications could increase the safety of those working alone, particularly in laboratory environments where various types of hazards may exist.

Risk review – NHM risk management system

The NHM uses a software called Rivo Safeguard (now on SpheraCloud) to record and manage risks. There are limits on the functionality of the current version, particularly in terms of searching or exporting data from within risk assessments, and details of incidents are protected personal data. This exercise therefore included:

- Discussion with relevant personnel e.g. the NHM Health and Safety team for their insights
- Examination of the categories of data / information within Safeguard to determine where relevant information or risk assessments might be found
- A manual examination of a sample of current risk assessments across relevant categories, to identify and capture relevant content
- Sorting of this content into thematic areas for further examination in relation to robotics and automated warehousing.

Data / information categories within the system

Key content categories within Safeguard are 'hazards', 'assessments', 'incidents', and 'risk assessments'.

Assessments and hazards relate solely to assessments of display screen equipment (DSE) for individuals, and resolution of related issues e.g. the provision of eye test vouchers for DSE users. These categories are therefore not relevant to automation or robotics - they apply to any environment where staff are using computers.

Incidents and risk assessments are covered in more detail below.

Incidents

1. Incidents in Safeguard record Health and Safety incidents and near misses, subdivided by relevant areas of the Museum organisation. Areas most relevant to collections and warehousing are Conservation, Life Sciences, Earth Sciences, Imaging and Analysis Centre (IAC), and Libraries.

2. Between January 2014 and August 2019, Safeguard recorded just over 150 incidents (accidents and near misses, excluding pre-existing medical conditions) across those areas, of which:

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- all but 8 involved employees (5 were departmental visitors and 3 were scientific associates);
- only 3 record any days lost as a result.

3. Summary data does not provide any details of incidents or causes, but examples checked by the NHM Health and Safety manager suggest the majority are related to factors such as slips, trips and falls, rather than directly to collections handling or similar.

4. Incidents in Safeguard therefore do not provide useful data for this report. However the NHM Health and Safety manager has suggested the following themes/areas which have been present in incidents over the years and may be relevant to future facilities and to automation:
    - Security (e.g. conditions around physical access to collections);
    - Manual handling
    - Environmental conditions including pest control

Risk assessments

5. Risk assessments are completed by staff in relation to all activities that may result in a health and safety risk, to record risks and mitigation. They therefore provide the key information for this evaluation of areas that may be relevant to robotics, automation and assistive technologies.

6. Risk assessments fall into the following categories in the system (selected by user), known as 'type' - those in bold are considered to be in scope for this project and are examined further below:
    - **NHM standard multi-hazard**
    - Manager's Health and Safety Control Processes
    - Fieldwork
    - **Manual Handling**
    - **Working Alone**
    - Young Persons (under the age of 18)
    - Quarterly local area safety inspection checklist (e.g. to check for risks in an office)
    - Business, Conference and Touring Exhibitions Travellers Risk Assessment (required if travelling outside EU)

7. Risk assessments are 'current' or 'archived' - this is at the discretion of the author. For this exercise, only current risk assessments were considered.

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8. As with incidents, risk assessments are further subdivided into areas of the organisation - NB there are more relevant categories for risk assessments than for incidents. These include some 'generic' ones for holding templates, and some projects - for one relevant completed project only, archived assessments were included.

9. Out of a longer list including many other Museum teams, the following areas involving collections were looked at - those in bold were found to have relevant current risk assessments for further investigation:

- Archives - no relevant current risk assessments
- **Conservation Centre**
- **Digital Collections Programme (DCP)**
- **Earth Science (ES) Collections**
- **ES Economic and Environmental Earth Sciences**
- **ES Invertebrates and Plants Paleobiology**
- **ES Mineral and Planetary Sciences**
- **ES Vertebrates and Anthropology Paleobiology**
- **Imaging and Analysis Centre**
- Invertebrates - obsolete category (see LS categories below)
- Invertebrates and Plants Curation Team A - obsolete category
- Invertebrates and Plants Curation Team B - obsolete category
- Invertebrates Curatorial Group - obsolete category
- Libary & Archives (LA) Collections Operations Division - no current risk assessments
- **LA Operations**
- LA Researcher Services and Digital Delivery - no current risk assessments
- LA special collections - no current risk assessments
- **Life Science (LS) Algae, Fungi & Plants**
- **LS Angela Marmont Centre (for UK biodiversity)**
- LS Collections - no current risk assessments
- **LS Department Operations Team**
- **LS Diversity and Informatics**
- **LS GENERIC on site**
- **LS Insects**
- **LS Invertebrates**
- **LS Parasites & Vectors**
- **LS Vertebrates**
- Molecular Biology Laboratories - no relevant current risk assessments
- **Molecular Biology Labs GENERIC**
- NHM - substances - obsolete category

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- Orthoptera Isoptera, Odonata, Trichopte - obsolete category
- **PROJECT - Anthropology Store Refurbishment**
- **PROJECT - Airless (archived assessment)**
- PROJECT - LA collections move - no risk assessments
- Science Admin Team - no current risk assessments
- Science Directorate - no relevant current risk assessments
- Science Resources - no current risk assessments
- **Tring (NHM's Museum and collections at Tring)**

10. For each area at (10) above, risk assessments were ordered by the 'type' to identify current risk assessments of the types shown in bold at paragraph (7). These lists were downloaded to a spreadsheet, identifying 642 potentially relevant risk assessments. Of these, the vast majority were the NHM standard multi hazard type, which is clearly used a default and has overlap with other types. Two were for working alone, and 15 manual handling.

11. All manual handling and working alone risk assessments were opened and manually reviewed.

12. Over 600 multi hazard assessments was too many for detailed examination in this project. In practice, however, many in fact were of other types - for instance it is possible in the title to identify fieldwork as the main focus. Other titles also gave good indication of relevance for instance it is possible to see which assessments focus on building work, behaviour of contractors or users and other areas which are not relevant to the potential for robotic and assistive technologies. A manual exercise was therefore carried out to identify the most relevant titles and examine these risks assessments in detail for the multi hazard type.

Results of the risk assessment review

Manual Handling

13. Screenshots of the Manual Handling risk assessment template are at appendix A. As well as text fields, this template includes sections with radio button lists which highlight possible areas for intervention in relation to task, environment, load and capability. In addition (not shown in the appendix) the template goes on to cover additional hazards; individuals with specific needs (e.g. disabilities, pregnancy); safe systems of work and control measures.

14. Fifteen risk assessments relating to manual handling were identified in our work, and these were all opened and reviewed. Of these, 9 were assessed as low and 3 as

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medium risk after control measures. 3 were not scored (e.g. because they are generic templates not specific assessments of risks in practice).

15. Areas covered in these templates were:
    - Moving, packing and lifting specimens and artworks
    - Handling heavy and/or bulky specimens or artworks
    - Moving and lifting equipment, furniture, boxes/storage and supplies
    - Acids (in practice this would expand to include many hazardous supplies, preservatives and specimens, whether chemical, radioactive etc)
    - Obstacles in routes e.g. bumps, ledges, narrow areas, turns
    - Handling drawers, trays, folders etc of specimens
    - Protruding drawers or handles and similar
    - Low/high storage areas and similar
    - Use and movement of of stepladders and similar
    - Working in compacterised storage areas
    - Use of roller racking
    - Temperature
    - Use of presses (e.g. in plant mounting)

16. Control/mitigation measures made reference to relevant Museum training, policies, relevant regulations and assistive kit. In particular, approaches used in manual handling may (subject to training and policies) include any of:
    - Trolleys
    - Hydraulic / scissor-lift trolleys
    - Cranes
    - Pallet and fork lift trucks
    - Skates
    - Hoists
    - Step ladders
    - Lifts (used instead of stairs where possible)
    - Extraction fans and hoods
    - Suitable height tables and similar
    - Wrapping and packing (e.g. to cover sharp or protruding areas while moving)
    - Personal Protective Equipment - clothes, footwear, gloves, high-vis, helmets etc
    - Use of trained staff including porters and specialise movers (contractors)
    - Working with colleagues e.g. to coordinate lifting by two or more people and to supervise such activity
    - Avoiding involving visitors or those with known health considerations in manual handling
    - Use of imaging / digitisation to reduce task recurrence

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17. It is clear that there are many unavoidable manual handling tasks and risks in working with collections, some of which are occasional e.g. only incurred during major moves, and some which recur regularly e.g. producing items on request for visitors/researchers.

18. Both the individual risk assessments, and the radio button lists in the template at Appendix A, suggest areas where robotic and assistive technologies could potentially add to solutions and control measures already mentioned above. All of the radio button areas are considered relevant to some of the templates reviewed. Machines are likely to have strengths relevant to human handling in relation to weight; environmental conditions; and repetitive handling. These benefits are likely to apply to repetitive tasks, but may not apply for example where space is restricted or where obstacles exist in routes.

Working alone

19. This template has text fields only, not 'built-in' categories or lists like manual handling. Fields cover description; named employees at risk; hazards to be added; specific needs; and safe system of work.

20. Only two working alone templates were identified in relevant areas and these were both opened and reviewed. These were both rated low risk after control measures. One related to working from home, identifying slip, trip or fall and fire or CO leak as the relevant hazards. The other related to lab work involving faecal matter, but included very few details of processes.

21. Overall, therefore, our exploration showed no clear evidence or examples in relation to working alone risks and whether these could be mitigated through robotics or automated handling.

22. It seems likely in general terms, however, that technologies such as environmental sensing and remote communications (radio, video or phone link) could increase the safety of those working alone, particularly in laboratory environments where various types of hazards may exist.

Multi-hazard

23. The Multi-hazard risk assessment 'type' offers primarily text fields to create and add hazards, covering description; hazards (with ratings); individuals with specific needs; safe system of work; related documents/tasks and review.

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24. Of the 625 multi-hazard risk assessments identified as relevant to this project, a selection of 37 was made for individual review, based on title information, e.g. excluding the many in which fieldwork of exhibition set up was a key emphasis; attempting to avoid duplication e.g. there are very similar risk assessments from different areas regarding use of knives/scalpels; and covering all the sampled organisational areas. Fieldwork was a key category for both Earth and Life Science risk assessments so the majority of these assessments were excluded.

25. These templates cover a wide range of areas from sections of Museum buildings; to use of specialist equipment; Specimen handling (by hand and otherwise e.g. with forceps etc); public events and so on. The key information in these templates are the hazards and control measures.

26. Relevant hazards identified include the following (it is notable that manual handling and working alone form hazards within multi-hazard, explaining why there are fewer of these templates alone):
    - Slips, trips and falls
    - Falling items
    - Damage to and breakage of specimens, kit etc
    - Spillage
    - Manual handling
    - Accidents or injury including back strain, RSI, crushing/pinching, becoming trapped
    - Electrical hazards including electric shock, power surges, incorrect supply/connection
    - Fire
    - Power failure
    - Explosion and explosive devices
    - Low/high temperatures (area or equipment, and consequences e.g. burns)
    - Working alone
    - Sharp tools or items (from knives to paper, and consequences e.g. cuts)
    - Suspicious packages
    - Abusive or violent behaviour
    - Inappropriate behaviour (to staff or collections)
    - High or low working including step ladders etc
    - Use of hazardous chemicals e.g. corrosive, flammable etc (includes glues and solvents, arsenic, ammonia, lead, mercury, ethanol, acids and others)
    - Biological hazards and pathogens e.g. work with cultures, spores, bird corpses etc
    - Use of X-ray emitting equipment
    - Dust inhalation

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- ○ Noise
- ○ Light sensitivity (e.g. lasers, flicker)
- ○ Theft (of collections, donations etc)
- ○ Leakage
- ○ Damage to building fabric
- ○ Risks to working outside, e.g. weather, wildlife, cliffs, tides, bites etc
- ○ Traffic accidents

27. Control/mitigation measures largely make reference to training, and to procedures and policies including detailed instructions for relevant equipment and similar. In addition to measures identified under manual handling above, such as personal protective equipment, approaches used may include any of:
    - ○ Carrying radio/phone
    - ○ Security practices e.g. sign in/out and patrols
    - ○ Keeping areas tidy and appropriate treatment of waste including clinical waste, chemical waste etc
    - ○ Correct use of designated areas, equipment and features (e.g. extraction cabinets, filters, wheel locks)
    - ○ Regular servicing of equipment/labs
    - ○ Environmental controls e.g. temperature, humidity
    - ○ Appropriate use of alarms e.g. in walk in freezers or for fire etc, and relevant response procedures e.g. evacuation
    - ○ Appropriate supervision
    - ○ Taking appropriate time / not rushing tasks
    - ○ Reporting incidents and near misses

28. Overall, the majority of risk types identified in this review show possibilities for improvement with automation, subject to cost-benefit analysis in particular instances. There are a smaller number of categories, however, where risks identified are likely to be the same or higher for robots as for humans, for example uneven floors, leakage, and power or electrical faults. For a fuller discussion see the summary above.

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Appendix 2 Annex 1 – Manual Handling risk assessment template extract

Manual handling risk assessment

Risk assessment title

Please enter a title for this assessment:

Task description

Can the task be avoided?

○ Yes, task can be avoided

● No, task cannot be avoided

Notes on task avoidance:

If you answered no above explain why the task cannot be avoided (for instance, 'No alternative solution' or 'Not reasonably practicable to use alternative'). If you answered yes explain how and when you are going to avoid the task being performed.

The Task

	N/A	Trivial	Tolerable	Substantial	Intolerable
Twisting / Stooping	●	○	○	○	○
Stretching / bending	●	○	○	○	○
Strenuous pushing / pulling	●	○	○	○	○
Repetitive handling	●	○	○	○	○
Long carry	●	○	○	○	○
Holding load away from trunk	●	○	○	○	○
Insufficient resting time / recovery	●	○	○	○	○

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The Environment

	N/A	Trivial	Tolerable	Substantial	Intolerable
Poor floors	◉	○	○	○	○
Uneven levels	◉	○	○	○	○
Restricted space	◉	○	○	○	○
Poor lighting	◉	○	○	○	○
Strong air movements	◉	○	○	○	○
Public areas	◉	○	○	○	○
Hot/cold/humid conditions	◉	○	○	○	○
Exposed to weather	◉	○	○	○	○

The Load

	N/A	Trivial	Tolerable	Substantial	Intolerable
Heavy	◉	○	○	○	○
Bulky / unwieldy	◉	○	○	○	○
Difficult to hold	◉	○	○	○	○
Unstable/unpredictable	◉	○	○	○	○
Intrinsically harmful e.g. sharp edges, hot, cold etc.	◉	○	○	○	○

Individual capability

	N/A	Trivial	Tolerable	Substantial	Intolerable
Risk level is dependent on capability of employee	◉	○	○	○	○
Risk to those with health problem	◉	○	○	○	○
Risk to those who are pregnant	◉	○	○	○	○
Risk to anyone untrained	◉	○	○	○	○
Movement hindered by PPE	◉	○	○	○	○

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