Robotic disassembly and autonomous remanufacturing

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2. Why remanufacture?
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1. What is Remanufacturing?

CRR - Centre for Remanufacturing and Reuse, Oakdene Hollins

http://www.remanufacturing.org.uk/index.php

- … the process of returning a used product to at least its original performance with a warranty that is equivalent to or better than that of the newly manufactured product. From a customer viewpoint, the remanufactured product can be considered the same as a new product.

ERN – European Remanufacturing Network

https://www.remanufacturing.eu/remanufacturing/about-remanufacturing/

Product lifecycle
Remanufacturing and the Circular Economy

https://twitter.com/EU_ENV/status/473860526926475264/photo/1
2. Why Remanufacture?

All-Party Parliamentary Sustainable Resource Group, 2014

- Even the most conservative estimates suggest that the potential of remanufacturing in the UK is £5.6billion.

- The United States is a leader in the field of remanufacturing, with China also recently investing heavily in the industry.

- Existing drivers that spur on remanufacturing include lower input costs and subsequent lower prices for customers, resource security and resilience in a volatile world, reduced carbon emissions and reduced water and energy use.


- A shift towards a circular economy could bring savings of €600bn for EU businesses, and reduce greenhouse gas emissions by 2 to 4% every year.
Energy and Material Savings

(Steinhilper 1998)
- More than 30,000 tons of metal recycled each year
- More than 40,000 tons of core returned to Meritor remanufacturing facilities annually
- More than 18,000 gearing units remanufactured annually
- Over 20,000 brakes shoes remanufactured daily
Why Remanufacture?

Favourable Environmental Footprint...

**Cylinder Head**

<table>
<thead>
<tr>
<th></th>
<th>Reman vs. New</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green House Gas</td>
<td>61% less</td>
</tr>
<tr>
<td>Water use</td>
<td>93% less</td>
</tr>
<tr>
<td>Energy use</td>
<td>86% less</td>
</tr>
<tr>
<td>Material use</td>
<td>90% less</td>
</tr>
<tr>
<td>Landfill space</td>
<td>&gt; 99% less</td>
</tr>
</tbody>
</table>

* 2006 Cat study, 3412 cylinder head
Win-win-win situation

- Manufacturers benefit
  - Cost: £ 35-60% of new
  - Energy: 20-25% of new

- The environment benefits

- Society benefits

Energy savings
- 233 oil tankers

Raw material savings
- 155,000 train carriages

Industry size
- Current: £2.7b
- Potential: £5.6b

www.hssmi.org © 2015
Disassembly in Remanufacturing

- Collected cores
- Disassembly
- Cleaning & Drying
- Repair & Testing
- Reassembly
- Shipped products

Collected cores lead to disassembly, which then goes to cleaning and drying. From there, it moves to repair and testing before being shipped as products.
CAT C-15 Engine Teardown
2. Aims and Vision

- Robotic disassembly to address bottleneck in remanufacturing.
- Fundamental understanding of disassembly processes to create robust autonomous disassembly systems.
- Scientific multi-disciplinary approach to disassembly problems to derive knowledge and understanding of disassembly.
Five work packages:

- **WP 1.** Disassembly science.
  
  Study disassembly processes to determine patterns recurring in disassembly problems and the physical and cognitive efforts needed.

- **WP 2.** Practical disassembly strategies.
  
  Develop accommodation strategies to enable robots to perform selected disassembly tasks autonomously.

- **WP 3.** Disassembly planning.
  
  Develop disassembly sequence planning and replanning systems using product CAD data and scientific planning rules.

- **WP 4.** Collaborative disassembly.
  
  Develop optimal collaboration strategies exploiting the complementarity of robots and humans to achieve complex operations.

- **WP 5.** Practical demonstrations.
## Disassembly Operation Survey

<table>
<thead>
<tr>
<th>Products</th>
<th>Electrical motors</th>
<th>Power hand tools</th>
<th>Automotive parts*</th>
<th>Engines</th>
<th>Small appliances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity</td>
<td>10</td>
<td>7</td>
<td>61</td>
<td>9</td>
<td>27</td>
</tr>
<tr>
<td>Total ops</td>
<td>294</td>
<td>192</td>
<td>1698</td>
<td>790</td>
<td>619</td>
</tr>
<tr>
<td>Unscrewing</td>
<td>165 (56.1%)</td>
<td>94 (49.0%)</td>
<td>646 (38.0%)</td>
<td>401 (50.8%)</td>
<td>245 (39.6%)</td>
</tr>
<tr>
<td>Separation</td>
<td>76 (25.9%)</td>
<td>43 (22.4%)</td>
<td>574 (33.8%)</td>
<td>212 (26.8%)</td>
<td>231 (37.3%)</td>
</tr>
<tr>
<td>Pulling</td>
<td>45 (15.3%)</td>
<td>51 (26.6%)</td>
<td>382 (22.5%)</td>
<td>161 (20.4%)</td>
<td>106 (17.1%)</td>
</tr>
</tbody>
</table>

* Excluding engines
## Disassembly Operation Survey

<table>
<thead>
<tr>
<th>Products</th>
<th>Domestic appliances</th>
<th>General mechanical products</th>
<th>Small devices</th>
<th>Miscellany</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quantity</strong></td>
<td>8</td>
<td>58</td>
<td>28</td>
<td>5</td>
</tr>
<tr>
<td><strong>Total ops</strong></td>
<td>247</td>
<td>1842</td>
<td>460</td>
<td>253</td>
</tr>
<tr>
<td><strong>Unscrewing</strong></td>
<td>120 (48.6%)</td>
<td>806 (43.8%)</td>
<td>113 (24.6%)</td>
<td>142 (56.1%)</td>
</tr>
<tr>
<td><strong>Separation</strong></td>
<td>58 (23.5%)</td>
<td>645 (35.0%)</td>
<td>195 (42.4%)</td>
<td>78 (30.8%)</td>
</tr>
<tr>
<td><strong>Pulling</strong></td>
<td>63 (25.5%)</td>
<td>354 (19.2%)</td>
<td>126 (27.4%)</td>
<td>23 (9.1%)</td>
</tr>
</tbody>
</table>
Disassembly Operation Survey

<table>
<thead>
<tr>
<th>Total Products</th>
<th>213</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Operations</td>
<td>6395</td>
</tr>
<tr>
<td>Unscrewing</td>
<td>2732 (42.72%)</td>
</tr>
<tr>
<td>Separation</td>
<td>2112 (33.03%)</td>
</tr>
<tr>
<td>Pulling</td>
<td>1311 (20.50%)</td>
</tr>
</tbody>
</table>
Modelling of disassembly operations

• Removal of Pins from Holes
  (Jamming, wedging)
• Separation of press-fit components
  (Hard contact, Frictional)
• Contact stress and deformations
  (Stress concentration, shape deflection)
• Strategies to prevent damage to components
  (Hydraulic disassembly, Thermal disassembly)
Geometric and Kinematic Modelling
Quasi-Static Modelling

\[ \sum M_A = 0 \quad f_B \cdot d + N_B \cdot l_{AB} - F_\theta \cdot \frac{d}{2} = 0 \quad (1) \]

\[ \sum M_B = 0 \quad -f_A \cdot d + N_A \cdot l_{AB} + F_\theta \cdot \frac{d}{2} = 0 \quad (2) \]

\[ \sum F_\theta = 0 \quad -f_A - f_B + F_\theta = 0 \quad (3) \]

From (1) & (2), \( N_B (\mu d + l_{AB}) = N_A (\mu d - l_{AB}) \),
From (3), \( F_\theta = \mu \cdot (N_A + N_B) \)
FEA simulation of peg-hole for robotic disassembly

Peg-in-hole with chamfers
- Insertion with chamfers (Jamming)
- Insertion using soft RCC (No jamming)

Separation: To remove bearing disc from drive shaft
- Pushing operation (Wedging)
- Pulling operation (No wedging)
Investigation of peg-hole separation

Rotating and pulling
0.166mm/s

Test stage

Straight pulling
1mm/s
Contact Stress Modelling

FEA element: Tetrahedral C3D20; Interaction: Surface contact with friction $\mu=0.1$; End push with internal pressure
• Autonomous and semi-autonomous disassembly
• Reactive strategies (Passive accommodation; active impedance)
• Deliberative strategies (Sensor-driven knowledge-based control; fuzzy logic control; ANFIS learning control)
• Blind search (Ultrasonic vibration)
Collaborative Disassembly

- Two forms of collaboration

- A hybrid disassembly line
Passive Accommodation - RCC

Remote Center Compliance Point
Cocking Misalignment
Lateral Misalignment

1. Single point contact force causes Compensator to shift laterally
2. Two point contact force causes Compensator to rotate
3. Remote Center Compliance Point
\[ m_a \ddot{x} + d_a \dot{x} + k_a x = f_u + F \]

\[ m_d \ddot{x} + d_d (\dot{x} - \dot{x}_d) + k_d (x - x_d) = F \]

\[ f_u = (m_a - m_d) \ddot{x} + (d_a - d_d) \dot{x} + (k_a - k_d) x + d_d \dot{x}_d + k_d x_d \]

\[ f_u = (d_a - d_d) \dot{x} + (k_a - k_d) x + d_d \dot{x}_d + k_d x_d \]
Collaborative Robots – Examples

A. Kuka
B. Baxter
C. Yumi
D. Fanuc
Disassembly Sequence Planning

Knowledge Library

Case Library

Resources Library

Results Library

Maintenance Product Information

Input

Feasibility Graph Construction

Graph 1

Improve Max-Min ant system

Product Disassembly Sequence Planning

Output

Product Disassembly Sequence

Assembly

Assembly

Graph 2
A matrix approach to selective disassembly sequence planning
- Disassemble target component in optimal disassembly route

Analyse product
1. Find parts that contact and are connected to the target component with a matrix.
2. Eliminate unnecessary disassembly parts by analyzing the properties of target component from the matrix.
3. Form new modules of the initial product.

Determine the direction and obstacle for disassembly
1. Find the disassembly direction of fasteners with matrix
2. Detect if any obstacle to be removed before disassembling the given fastener

Evaluate the optimal disassembly sequence
1. Matrices’ rule to form feasible disassembly sequences
2. Guideline to optimise the disassembly sequence

Remove target component
Disassembly Sequence Planning – Example

Disassembly Sequences of Water Pump

Level 0

(1) A B C
    D E F

(2) A B C
    D E F

(3) A B C
    D E F

Level 1

(1) A B C
    D E F

(2) A B C
    D E F

(3) A B C
    D E F

Level 2

(1) A B C
    D E F

(2) A B C
    D E F

(3) A B C
    D E F

Level 3

(1) A B C
    D E F

(2) A B C
    D E F

(3) A B C
    D E F

Level 4

(1) A B C
    D E F

(2) A B C
    D E F

(3) A B C
    D E F

Level 5

(1) A B C
    D E F

(2) A B C
    D E F

(3) A B C
    D E F
Disassembly process flow design

1. **Product**
   - Image acquisition
   - Product Identification and Assessment
   - Database

2. **Suitable for Disassembly?**
   - **YES**
     - Robot arms securing position of product with fixture
     - Automated Disassembly
   - **NO**
     - Robot arm transfers product to **Human Workstation**
     - Unsuccessful Disassembly/Complications
     - Further assessment of product by human operator
     - Manual Disassembly

3. **Robot Workstation**
   - Separated components are sorted accordingly and transferred to the **End** zone

4. **Human Workstation**
Screw drive design and unfastening effort

- Evaluate optimum screw drive design based on minimal disassembly time to minimise labour and resources cost
  - 10 common screw drive designs

<table>
<thead>
<tr>
<th>Types of Screw Drives</th>
<th>Mean Effort Ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torx</td>
<td>13.090</td>
</tr>
<tr>
<td>Philips Square</td>
<td>10.916</td>
</tr>
<tr>
<td>Double Square</td>
<td>9.947</td>
</tr>
<tr>
<td>Slotted</td>
<td>9.396</td>
</tr>
<tr>
<td>Philips</td>
<td>8.792</td>
</tr>
<tr>
<td>Frewarson</td>
<td>8.020</td>
</tr>
<tr>
<td>Clutch</td>
<td>3.402</td>
</tr>
<tr>
<td>Hex</td>
<td>3.133</td>
</tr>
<tr>
<td>Robertson</td>
<td>2.680</td>
</tr>
<tr>
<td>TA</td>
<td>2.676</td>
</tr>
</tbody>
</table>

- Force analysis
Vision recognition of mechanical parts

Training Image stored in database with Feature Descriptors

Successful match of Product with Training Image
Robotic Disassembly Cell

Robotic Disassembly Cell (Semi-Autonomous, Human-Robot Collaborative)

Products
- Controller
  - Controller, smartPAD, PC
- Vision
  - Camera, kinect devices
- Sensors
  - Force / Torque sensor
- Manipulators
  - KUKA LBR iiwa 14 R820 x 2
- Human
  - Hands, eyes, brain
- Tools
  - Gripper, unscrewdriver, press machine, etc.
- Fixtures
  - Workbench, fixtures, position devices

Parts / Components of Products
Robotic Disassembly Cell – Water Pump
4. Remanufacturing and Re-distributed Manufacturing

- Uncertainties in remanufacturing – *Quality, quantity* and *timing* of returned cores and variability in processing times
- Reduction or elimination of uncertainties with IoT technologies
- Smart embedded sensing, tracking and communication devices
- Continuous monitoring of machine and product condition
- Accurate prediction of *Remaining Useful Life*
- Complete record of lifecycle data for a product
- Potential to use data collected from past lifecycles to help effective deployment of remanufactured products

Goods visibility: cloud-based GPS and RFID technologies providing identity, location, and other tracking details of goods in storage and transit;

Fleet visibility: telematics using real-time sensor information and environmental data (weather and traffic) to increase agility and efficiency.

http://cerasis.com/2014/02/19/what-is-reverse-logistics/
http://www.amertranslogistics.com/services/reverse-logistics/
4. RFID in the Supply Chain – from Manufacturer to Retailer

https://www.iotuniversity.com/2016/04/rfid-enabled-supply-chain-visibility/
5. Team: UoB

- Dr Chunqian Ji, Senior Research Fellow
- Dr Shizhong Su, Senior Research Fellow
- Dr Yongjing Wang, Research Fellow
- Dr Jun Huang, Research Fellow
- Dr Yilin Fang, Visiting Academic
- Dr Jun Guo, Visiting Academic
- Dr Xuemei Jiang, Visiting Academic
- Jiayi Liu, Visiting PhD Researcher
- Soran Parsa, PhD Researcher
- Senjing Zheng, PhD Researcher
- Dr Robert Cripps
- Dr Mozafar Saadat
- Dr Marco Castellani
- Dr Khamis Essa
## 5. Team: Partners

<table>
<thead>
<tr>
<th>Users</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caterpillar</td>
<td>▪ Advisory board</td>
</tr>
<tr>
<td></td>
<td>▪ Industrial validation</td>
</tr>
<tr>
<td></td>
<td>▪ Product/component provision</td>
</tr>
<tr>
<td></td>
<td>▪ Exploitation</td>
</tr>
<tr>
<td>Meritor</td>
<td></td>
</tr>
<tr>
<td>MG Motor</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Technology Translators</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSSMI</td>
<td>▪ Advisory board</td>
</tr>
<tr>
<td></td>
<td>▪ Technical input</td>
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<tr>
<td></td>
<td>▪ Collaborative research</td>
</tr>
<tr>
<td></td>
<td>▪ Dissemination</td>
</tr>
<tr>
<td>MTC</td>
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</tr>
</tbody>
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### 5. Team: International Partners

<table>
<thead>
<tr>
<th>Universities</th>
<th>Focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wuhan University of Technology, China</td>
<td>- Disassembly planning</td>
</tr>
<tr>
<td>(Professor Zude Zhou; Professor Quan Liu; Dr Wenjun Xu)</td>
<td>- Disassembly economics</td>
</tr>
<tr>
<td>University of Castilla-La Mancha, Spain</td>
<td></td>
</tr>
<tr>
<td>(Dr Francisco Javier Ramírez Fernandez)</td>
<td></td>
</tr>
</tbody>
</table>
5. Team: Autonomous Remanufacturing (AutoReman) Network

Join us for free.

Email: autoreman@contacts.bham.ac.uk

Web: http://autoreman.altervista.org/index.html

Karmenu Vella - *With the circular economy, we are looking at a triple win. Society can win through job creation, savings for businesses and lower carbon emissions. It’s a major opportunity – let’s make sure we grasp it.*