Autonomous remanufacturing enabled by robotic disassembly (and Industry 4.0)

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University of Birmingham

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1. What is remanufacturing and why remanufacture?
2. Robotic disassembly: the AutoReman programme
3. Industry 4.0
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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/

## Why Remanufacture?

All-Party Parliamentary Sustainable Resource Group, 2014

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

- 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

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...

<table>
<thead>
<tr>
<th>Cylinder Head</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 Caterpillar, 3412 cylinder head

Win-win-win situation

- Manufacturers benefit
  - £5 35-60% of new
- The environment benefits
  - Energy 20-25% of new
- Society benefits

Win-win-win situation

- Energy savings
  - 233 oil tankers
- Raw material savings
  - 155,000 train carriages
- Industry size
  - £2.7b Current
  - £5.6b Potential
Disassembly in Remanufacturing

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

CAT C-15 Engine Teardown

- Image of a person working on an engine
2. Robotic Disassembly and AutoReman

- 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.

3. Research Programme and Interim Results

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

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**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>Quantity</td>
<td>8</td>
<td>58</td>
<td>28</td>
<td>5</td>
</tr>
<tr>
<td>Total ops</td>
<td>247</td>
<td>1842</td>
<td>460</td>
<td>253</td>
</tr>
<tr>
<td>Unscrewing</td>
<td>120 (48.6%)</td>
<td>806 (43.8%)</td>
<td>113 (24.6%)</td>
<td>142 (56.1%)</td>
</tr>
<tr>
<td>Separation</td>
<td>58 (23.5%)</td>
<td>645 (35.0%)</td>
<td>195 (42.4%)</td>
<td>78 (30.8%)</td>
</tr>
<tr>
<td>Pulling</td>
<td>63 (25.5%)</td>
<td>354 (19.2%)</td>
<td>126 (27.4%)</td>
<td>23 (9.1%)</td>
</tr>
</tbody>
</table>

---

* Excluding engines
Disassembly Operation Survey

<table>
<thead>
<tr>
<th>Operation</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Products</td>
<td>213</td>
</tr>
<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)
From (1) & (2), \( N_B(\mu d + l_{AB}) = N_A(\mu d - l_{AB}) \).

From (3), \( F_B = \mu \cdot (N_A + N_B) \).
*FEA simulation of peg-hole 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)

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**Investigation of peg-hole separation**

- **Rotating and pulling** 0.166mm/s
- **Straight pulling** 1mm/s

**Test stage**
Contact Stress Modelling

FEA element: Tetrahedral C3D20; Interaction: Surface contact with friction \( \mu = 0.1 \); End push with internal pressure.

Strategies for Collaborative Disassembly

- 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
**Impedance Control**

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

**Collaborative Robots – Examples**

- A. Kuka
- B. Baxter
- C. Yumi
- D. Fanuc
A matrix approach to selective disassembly sequence planning

- Disassemble target component in optimal disassembly route

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

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

3. Evaluate the optimal disassembly sequence
   - Matrices’ rule to form feasible disassembly sequences
   - Guideline to optimise the disassembly sequence

Remove target component
Disassembly Sequence Planning - Example

Disassembly Sequences for Water Pump

Level 0

Level 1

Level 2

Level 3

Level 4

Level 5

Disassembly process flow design
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>Frearson</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**

- **Products**
  - Controller: KUKA LBR iiwa 14 R820 x 2
  - Vision: Camera, kinect devices
  - Sensors: Force / Torque sensor

- **Robotic Disassembly Cell**
- **Manipulators**
  - KUKA LBR iiwa 14 R820 x 2
- **Human**
  - Hands, eyes, brain
- **Tools**
  - Gripper, unscrewdriver, press machine, etc.
- **Fixtures**
  - Workbench, fixtures, position devices

**Robotic Disassembly Cell – Water Pump**

- Operator
- Press machine
- Water pump
- Robot
- Fixtures
- gripper
- Collection boxes
- Parts
### 3. Industry 4.0

#### Issues in Remanufacturing:

**Uncertainties**

- Supply uncertainties: quality, quantity and timing of returned cores
- Operational uncertainties: variability in processing (disassembly, repair or rebuild) routes and times
- Demand uncertainties: technology development and market changes

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#### Industry 4.0 Solutions:

**Reduction or elimination of uncertainties**

- 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
- Effective deployment of remanufactured products using past lifecycle data

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**B Esmaeilian, S Behdad and B Wang (2016)**

The evolution and future of manufacturing: A review

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### 3. Industry 4.0

#### Issues in Remanufacturing:

- Small production batches – batch sizes of 1 in MTO environments not uncommon
- Complicated materials management and resource planning
- Complex shop floor scheduling and control
- Inaccurate prediction of delivery date/long delivery times

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#### Industry 4.0 Solutions:

- Smart automation to facilitate customised remanufacturing
- Smart sensing and tagging to increase visibility of materials in storage and in transit
- Accurate reliability modelling to predict quality, quantity and type of components salvaged from cores
- Increased communication to enable close coordination between core acquisition, shop floor operations and sales
Industry 4.0 and Reverse Logistics

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

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

Goods visibility (internal): information systems to promote materials visibility to simplify materials management, resource planning and shop floor control

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4. Conclusion

- Robotic disassembly is an enabler of autonomous remanufacturing
- There are many uncertainties in remanufacturing
- They are caused by both a lack of information and a lack of communication
- Industry 4.0 technologies (smart sensing, smart products, communication, modelling, Big Data, cyber-physical production) can provide the information, connectivity and visibility needed to reduce or eliminate uncertainties
**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, Co-investigator
- Dr Mozafar Saadat, Co-investigator
- Dr Marco Castellani, Co-investigator
- Dr Khamis Essa, Co-investigator

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**Team: Partners**

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

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

<table>
<thead>
<tr>
<th>Universities</th>
<th>Focus</th>
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</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 (Dr Francisco Javier Ramírez Fernandez)</td>
<td></td>
</tr>
</tbody>
</table>

Team: Autonomous Remanufacturing (AutoReman) Network

Join us for free.

Email: autoreman@contacts.bham.ac.uk

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

Demo: https://www.youtube.com/watch?v=hgEeY_gwsG0&t=10s

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.