Institution: University of Sheffield		
Unit of Assessment: B-12 Engineering		
Title of case study: Transforming the Midea Group		
Period when the underpinning research was undertaken: 2008–2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Zi-Qiang Zhu	Professor	1989–present
Period when the claimed impact occurred: August 2013–July 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

Sheffield's research into permanent magnet brushless motor design, manufacture and control has been integrated by the Midea Group (world's largest manufacturer of consumer appliances) into the production of over 300 million motors per annum. The research has underpinned Midea's development of entire product ranges of domestic appliances and air conditioning systems, directly increasing their revenue by CNY7.5bn (≈£825m) since August 2013. Critically, our strategic combination of research leadership, new technology development, and knowledge and IP transfer has underpinned Midea Group's transformation from a consumer appliances manufacturer to a Fortune Global 500 creative technology group and validated expansion into a new sector, industrial automation, by the acquisition of the KUKA and Servotronix companies.

2. Underpinning research (indicative maximum 500 words)

The Electrical Machines and Drives (EMD) Research Group at Sheffield (led by Professor Zhu) is a global leader in the design and control of novel high torque/power density and high efficiency permanent magnet machines and drives for a wide range of market sectors. In 2010, this expertise attracted interest from the Midea Group that has strengthened and seen Sheffield undertake an extensive portfolio of research into foundational, core, and prospective technology for domestic appliances and industrial automation systems (worth £2.35m). As a result, between 2011 and July 2020 Midea has been granted, with Sheffield inventors, 78 patents, including 37 invention patents and 2 international patents **[S1]**. Specifically, Sheffield has addressed major research challenges surrounding motor topologies; intelligent sensorless, flux-weakening and speed control strategies; and design, material, and manufacturing process optimisation.

Domestic appliances

Examples of our research addressing key challenges and subsequent applications:

Sensorless control technology: Sheffield research **[R1, R2] [S3a]** developed ways to reduce appliance size and cost, and improve reliability through the use of sensorless control technology by:

a) Identifying the initial rotor position.
b) Compensating parasitic effects due to inverter nonlinearity utilising positive sequence current response for the first time.
c) Identifying optimal injected voltage waveform, magnitude, and frequency.

d) Parameter identification (particularly due to temperature rise, magnetic saturation variation due to load change, and inertia) for clothes auto-weighing, system friction, etc.

Midea first applied this technology to washing machines but it is now used across almost the entire product range.

Flux weakening technology: Whilst permanent magnet brushless motors have numerous advantages, they have a narrow constant power speed range, which limits application. This was improved through research into flux weakening technology **[R2, R3]** which addressed:

a) Parameter identification.
b) Novel control techniques for deep flux weakening to overcome instability.
c) New overmodulation technique involving full utilisation of the DC-link voltage.

The resulting step-change increase in motor speed range ratio from 1:3 (suitable for electric vehicles) to between 1:10 and 1:30 has been applied by Midea to their washing machine range.

Noise and vibration: Sheffield's research to reduce electromagnetic induced noise and vibration **[R3, R4, R5]** include:

a) Random pulse width modulation switching, leading to the application of pseudo-random high frequency signal injection, which is feasible to implement on low-cost microprocessors.
b) Analysis and detection of unbalanced magnetic force, leading to the development of a successful out-of-balance detection technique developed from the motor speed ripple and torque pulsation.
c) Robust design and minimisation of torque ripples caused by manufacturing tolerances.

This has enabled sensorless starting and quieter operation for Midea's washing machines.

Novel modular stator techniques: Sheffield's research into novel modular stator techniques **[R5, R6]** increased motor quality and performance whilst reducing labour and materials costs by:

a) Developing a patented system **[S3b]** to manufacture stators in segments to allow automated winding of copper coils and thus save labour costs and maintain consistency.
b) A novel modular structure and optimal design with nested components resulting in significantly reduced material usage (up to 40% less).
c) Improved packing factor resulting in reduced copper loss, improved thermal performance and increased torque density.

Midea used this research and applied it to their air-conditioning products as well as servo motors.

Design optimisation: The Sheffield group applied modern numerical optimisation techniques at the motor and drive system level to improve the efficiency and torque density (and therefore reduce the size) of almost all existing Midea Group products **[S1]**, including conventional universal motors, induction motors, and new permanent magnet motors.

Industrial automation systems

The Sheffield team also developed high-end mass-produced industrial servo motors and drives, drawing on research into modular stator technology. The research developed new motor structures **[R6] [S3c]** and techniques to eliminate parasitic effects such as induced voltage spikes by optimising the stator slot openings and rotor iron bridges **[R4]**; shaft leakage flux by employing a novel rotor of two offset parts **[R6]**; and by developing motor topologies less sensitive to variations in design parameters **[R5]**. These improvements led to novel topologies for stators (to simplify manufacture and reduce cost) and rotors (to improve the life of products by eliminating the shaft flux leakage and induced voltage spikes that cause bearing and inverter

damage) **[R4, R6]**. These changes have been implemented in servo control systems developed for automation systems, which are now in mass production by Servotronix.

3. References to the research (indicative maximum of six references)

University of Sheffield staff and students in **bold**

R1. **Zhu, Z. Q.,** & **Gong, L. M.** (2011). Investigation of Effectiveness of Sensorless Operation in Carrier-Signal-Injection-Based Sensorless-Control Methods. *IEEE Transactions on Industrial Electronics, 58*(8), 3431–3439. https://doi.org/10.1109/tie.2010.2081960. Cited by 120. (L.M. Gong was a Sheffield PhD student (2008-2011), then joined Midea in 2012 and is now Head of Midea GMCC & Welling Shanghai Electric Motor R&D Division).

R2. **Liu, K.,** & **Zhu, Z. Q.** (2015). Mechanical Parameter Estimation of Permanent-Magnet Synchronous Machines With Aiding From Estimation of Rotor PM Flux Linkage. *IEEE Transactions on Industry Applications, 51*(4), 3115–3125. https://doi.org/10.1109/tia.2015.2399615. Cited by 42.

R3. **Wang, C.,** & **Zhu, Z. Q.** (2020). Fuzzy Logic Speed Control of Permanent Magnet Synchronous Machine and Feedback Voltage Ripple Reduction in Flux-Weakening Operation Region. *IEEE Transactions on Industry Applications, 56*(2), 1505–1517. https://doi.org/10.1109/tia.2020.2967673. Cited by 2. (C. Wang was a Midea engineer (2011-2015) and a Sheffield PhD student (2015-2019), then re-joined Midea in 2019).

R4. **Zhu, Z. Q., Wu, D.,** & **Ge, X**. (2016). Investigation of Voltage Distortion in Fractional Slot Interior Permanent Magnet Machines Having Different Slot and Pole Number Combinations. *IEEE Transactions on Energy Conversion, 31*(3), 1192–1201. https://doi.org/10.1109/tec.2016.2553140. Cited by 14. (D. Wu was a Midea engineer (2011-2012) and a Sheffield PhD student (2012-2015), then re-joined Midea in 2015 and is now Head of Midea GMCC & Welling Strategic Motor Products Division). (X. Ge was a Midea engineer (2011-2014) and a Sheffield PhD student (2014-2016), then re-joined Midea in 2016).

R5. **Ge, X.,** & **Zhu, Z. Q. (**2017). Influence of Manufacturing Tolerances on Cogging Torque in Interior Permanent Magnet Machines with Eccentric and Sinusoidal Rotor Contours. IEEE Transactions on Industry Applications, 53(4), 3568–3578. https://doi.org/10.1109/tia.2017.2693264. Cited by 15.

R6. **Ge, X., Zhu, Z. Q.,** Li, J., & Chen, J. (2016). A Spoke-Type IPM Machine With Novel Alternate Airspace Barriers and Reduction of Unipolar Leakage Flux by Step-Staggered Rotor. IEEE Transactions on Industry Applications, 52(6), 4789–4797. https://doi.org/10.1109/tia.2016.2600649. Cited by 34.

4. Details of the impact (indicative maximum 750 words)

Midea became a Fortune Global 500 company in 2016 and is now the world's leading domestic appliance manufacturer. It has 34 production centres and over 150,000 employees, with sales in over 200 countries generating an annual revenue of more than CNY279bn (≈£30.7bn) in 2019 **[S1]**. However, prior to 2010 the Vice President and CTO of Midea Group stated, "*The Midea Group had very little internal R&D capability"* **[S1]**.

The Vice President and CTO confirmed, "*We sought out Professor Zhu and his team because of his world-leading research expertise in electrical machines and drives*" **[S1]**. In 2010, Professor Zhu became Adjunct Director **[S1, S2]** and since then, in addition to restructuring Midea's innovation system, he established and led three research and development platforms **[S1]**. The Vice President and CTO stated, "*Professor Ziqiang Zhu has made an irreplaceable contribution*

to the growth of Midea from solely a manufacturing company to a world-leading creative technology group through development of strategic planning, key technologies, core products, field expansion, and talent introduction." **[S1]**.

The Vice President and CTO stated, "*Innovations developed from Sheffield research have been incorporated across our entire product range, both in domestic appliances (over 300 million motors every year) and air conditioning systems*." **[S1] [R1-6]**. He continued, "*The work of Professor Zhu and his EMD Group has generated huge operating value for Midea Group, directly increasing revenue by ¥7.5bn (≈£825m) between 1st August 2013 and 31st July 2020*." **[S1]** Specifically, CNY2bn (≈£220m) from washing machines, CNY3.5bn (≈£385m) from air conditioning, CNY1bn (≈£110m) from refrigerators, CNY500m (≈£55m) from other appliances, and CNY500m (≈£55m) from servo systems **[S1]**.

Increased research capacity through innovative R&D platforms and personnel

The first element in the collaboration between Sheffield and Midea was the establishment in 2011 of the Mechanical and Electrical Business Division's R&D facility called the Midea Welling Shanghai Electric Motor Research Centre, under the close supervision of Professor Zhu **[S2]** and a former employee of the Sheffield EMD group (Deputy Director). Since August 2013, the number of researchers at the Shanghai centre has increased from 34 to 117 and according to the Vice President and CTO, "*making it the largest advanced R&D centre on electrical machines and drives in China.*" **[S1]**. Throughout this expansion, he continues, "*Professor Zhu has maintained strategic oversight throughout the process and continues to set the direction of the research centres, drawing on the latest Sheffield research to steer the Group's strategy*" **[S1]**.

In 2016, the Midea Group established a corporate-level research centre that conducted fundamental research on electrical drives and controls (EDC) and continued to draw on Sheffield's research. In 2017, the Sheffield-Midea Joint Research Laboratory (now Sheffield-Midea Electrical Machines and Control Systems Research Centre) was created at the University of Sheffield to extend Midea funded EDC research **[S1]**.

Midea sponsors an "Engineer of the Year" staff member to conduct a PhD in Sheffield (3 graduated, 5 currently studying) and has sponsored 6 project specific PhDs. The company employs 8 Sheffield alumni in senior positions, including two consecutive heads of the Shanghai centre, the General Manager of Midea's Automotive Components Division, Head of Strategic Motor Products Division and senior/principal engineers and team leaders across the group **[S1]**.

Product development

Sheffield's novel drive control and motor design and sensorless control technologies have been applied across the Midea Group's full domestic appliance range (washing machines, air conditioners, vacuum cleaners, refrigerators) and have resulted in reductions in the cost, weight, and size of motors as well as increased reliability **[R1, R2, S3a]**. The Vice President and CTO confirmed this has led to, "*a reduction of 30% in washing time for front-loading machines, and an increase in motor efficiency from 27% to 60%. The torque density of existing motors, even for conventional universal motors, is generally improved by 10% by employing a new global optimisation technique with no increase (even some reductions) in cost.*" **[S1]**.

The Vice President and CTO continued, "*Research into high-speed motors and sensorless control technology (particularly sensorless starting and quieter operation) has directly enabled the launch of a number of new products. These include vacuum cleaners; our flagship fully-automated Little Swan 'Beverley II series' washing machine (turnover ¥620m [≈£68.2m] since launch in 2016); and novel segmented stators for air conditioning units (reducing production costs by 10%, saving the group some ¥1.2bn [≈£132m] and reducing manufacturing time by 30%).*" **[S1] [R1, R2, R3, S3a, S3b]**. The high-end appliance Little Swan relies on sensorless

control technology developed at Sheffield to estimate load weight and distribution, amount of water, and detergent needed, making its operation extremely efficient, and silent **[S1]**.

Expansion into a new sector

The Vice President and CTO stated, *"Sheffield's core research expertise in electrical machines has allowed the Group to expand into the fast-growing industrial automation sector. Research into motion control and servo systems undertaken by Sheffield and under Professor Zhu's direction in Shanghai led to the development of high-performance rotary servo systems which were implemented on a trial basis on our production lines leading to savings of ¥3.5b [≈£385m] in labour costs and wastage."* **[S1] [R4, R5, R6, S3c]**. This represented a radical extension of Midea's core business into the fast-growing sector of drive controls, which are a key component of industrial automation and crucial to Industry 4.0.

The Vice President and CTO continued, "*It was this new research strength and proficiency in the sector that provided the Midea Group with the confidence we needed to take over German industrial automation specialist KUKA in 2016 and Israeli firm Servotronix (specialised in linear servo systems) in 2017"* **[S1]**. These acquisitions have allowed Midea Group to take a position in these expanding and hi-tech sectors and earn a combined revenue of CNY78bn (≈£8.6bn) to date **[S4] .** Since this acquisition, the systems developed from Sheffield research have been incorporated into Servotronix's offerings, significantly extending their product range and generating additional sales of CNY500m (≈£55m) **[S1]**.

5. Sources to corroborate the impact (indicative maximum of 10 references)

S1. Confidential testimonial letter from the Vice President and CTO of Midea Group (2020). Corroborates a) Midea's desire to work with Professor Zhu, b) Professor Zhu's strategic role in transforming Midea's R&D strategy and products, c) setting up the joint Midea-Sheffield R&D centre in Sheffield, d) Midea-Sheffield patents, e) economic impact, f) creation of talent pipeline, g) annual motor production, h) specific technology developments, i) specific productivity and process improvements, j) new product launches & k) role in new market expansion.

S2. Various evidence sources detailing Professor Zhu's ongoing role at Midea including https://bit.ly/3d2PymX (accessed 15th July 2020).

S3. Midea patents with Professor Zhu as named inventor. (Accessed 9th Feb 2021).

a) Gong, L., Sun, J., Xu P. & **Zhu, Z.Q.**, 2015. Method and device for identifying polarity of rotor of motor. Midea, CN104506105A. (Granted 2018). Used in intelligent washing machines. (Original in Chinese). http://bit.ly/38HDLJz

b) Chen, J., Sun, H., Wang, F. Zhu, T. & **Zhu, Z.Q.**, 2013. A stator structure for a single-phase induction motor employing concentrated windings. Midea, CN202817928U. (Granted 2013). Used for modular stators. (Original in Chinese). http://bit.ly/3bMagrU

c) Chen, J., Ge, X. & **Zhu, Z.Q.**, 2015. Permanent magnet motor and rotor thereof. Midea, CN104821673A. (Granted 2018). Used in servomotors. (Original in Chinese). http://bit.ly/3rRjSqX

S4. Midea Group Financial Highlights webpage - Annual - Segment Information. Corroborates Midea revenue for the robotics and automation system market segment (2016-2019). (Accessed 26th Jan 2021). https://www.midea-group.com/Investors/financial-reports