Institution: Coventry University

Unit of Assessment: 15

Title of case study: Control engineering applied to radiotherapy

1. Summary of the impact

This case study presents the applied research work in systems modelling, control and machine vision led by Dr **Haas** and its impact on radiotherapy. The research is linked to a series of collaborative projects with industry and the NHS on control systems development for clinical equipment, and the evaluation of state of the art treatments. The main impacts are:

- **Health impacts and impact on clinical technologies**: i) the realisation of the Total Skin Electron Betatron Unit, which is a unique skin cancer treatment machine, ii) the development of methods and devices to evaluate the capabilities of medical equipment for adaptive and image-guided radiotherapy thereby contributing to its clinical deployment.
- **Impact on practitioners and professional services**: the initiation of a culture change by encouraging the use of computer simulation tools and increased application of control theory in industry and the NHS.

2. Underpinning research

The underpinning research described in this case study is multidisciplinary in nature but exploits the control systems work of Dr **Haas** and Professor **Burnham** over the last 20 years at Coventry University. The research has focussed on the use of systems modelling, control and optimisation to deliver targeted radiotherapy treatments in collaboration with University Hospitals Coventry and Warwickshire NHS Trust (UHCW) and global medical technology companies.

The initial radiotherapy research led to the first UK demonstration of intensity modulated radiation therapy [1]. The focus of the research was then moved, through £43k funding from UHCW to finding a good but more importantly practical solution, from a clinical perspective [2]. In parallel, Coventry University took the lead in organising with UHCW the 'Coventry Cancer Challenge' and turned the Total Skin Electron Betatron Unit (TSEBU) ´from an idea into something real', see Figure 1. **Haas** used simulation studies to identify the most appropriate set up and then implemented the control system. **Haas** and **Burnham**’s ability to undertake research which delivered practical solutions attracted interest from Elekta, the second largest manufacturer of radiotherapy treatment devices in the world. This led to the highly successful £90k TCS/KTP 3787, 2002-04 (awarded Grade 1 and KTP Prize in 2005) to model a patient support system and design of a new control system for the development of dynamic therapy.

These projects established **Haas** and **Burnham**’s reputation and expertise in control applied to radiotherapy. The medical imaging research subsequently undertaken by **Haas** created the perfect blend of skills required for image guided and adaptive radiotherapy. This led **Haas** to be invited to take part in the 4.5 year €7M MAESTRO EU project involving 25 partners from 9 countries including 5 companies, 8 clinics and 12 research centres. **Haas** coordinated work package 1, entitled "Adaptive radiation delivery tracking and control for radiotherapy". A control engineering approach was used to develop a new integrated motion prediction [3, 4] and model predictive control system [5] to compensate patient and target motion using a robotic patient support system. **Haas** and **Burnham**’s team developed an artificial neural network [3], model based Kalman filters and interactive multiple model [4] predictors to anticipate tumour motion, thereby cancelling out the inherent systems lags and delays. Rapid prototyping and hardware in the loop techniques were exploited to successfully implement the controller on a clinical as well as a research system [5]. A novel electromechanical anatomical radiotherapy phantom was developed to simulate concurrent tumour and chest motion and evaluate the overall motion compensation strategy [6], see Figures 2a,c overleaf.

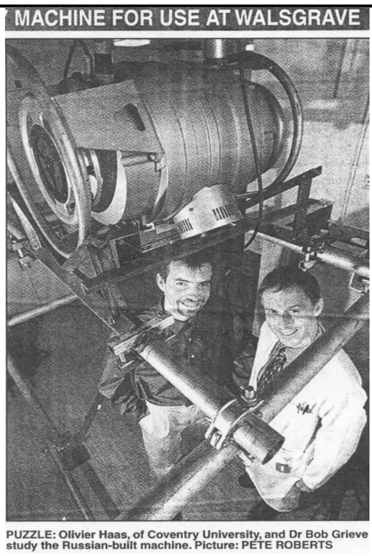
 MACHINE FOR USE AT WALSGRAVE PUZZLE: Olivier Haas, of Coventry University, and Dr Bob Grieve study the Russian-built machine. Picture: PETE ROBERTS	
a) Coventry Cancer Challenge	b) Current Total Total Skin Electron Betatron Unit

Figure 1: From a Betatron on a scaffolding (1997) to a clinical treatment machine at University Hospital Coventry and Warwickshire (2013)

3. References to the research

1. **Haas**, O.C.L., **Burnham**, K.J., Mills, J.A. (1998) 'Optimization of beam orientation in radiotherapy using planar geometry', Physics in Medicine and Biology, 43 (8), pp. 2179-2193 (Cited by 74, impact factor: 2.701)
2. Meyer, J., Mills, J.A., **Haas**, O.C.L., **Burnham**, K.J., Parvin, E.M. (2001) 'Accommodation of couch constraints for coplanar intensity modulated radiation therapy', Radiotherapy and Oncology 61 (1), pp. 23-32 (Cited by 17, impact factor: 4.520)
3. Goodband, J. H., **Haas**, O. C. L., and Mills, J. A. (2008) 'A Comparison of Neural Network Approaches for on-Line Prediction in IGRT.'. Medical Physics , 35 (3), 1113-1122 (Cited by 9, impact factor: 2.84)
4. Putra, D., **Haas**, O. C. L., Mills, J. A., and **Burnham**, K. J. (2008) 'A Multiple Model Approach to Respiratory Motion Prediction for Real-Time IGRT'. Physics in Medicine and Biology, 53 (6), 1651-1663 (Cited by 18, impact factor: 2.701)
5. **Haas**, O. C. L., Skworcow, P., Paluszczyszyn, D., Sahih, A., Ruta, M., and Mills, J. A. (2012) 'Couch-Based Motion Compensation: Modelling, Simulation and Real-Time Experiments'. Physics in Medicine and Biology, 57 (18), 5787-5807 (Cited by 1, impact factor: 2.701)
6. Depuydt, T., Verellen, D., **Haas**, O., Gevaert, T., Linthout, N., Duchateau, M., Tournel, K., Reynders, T., Leysen, K., Hoogeman, M., Storme, G., and Ridder, M. D. (2011) 'Geometric Accuracy of a Novel Gimbals Based Radiation Therapy Tumor Tracking System'. Radiotherapy and Oncology, 98 (3), 365-372 (Cited by 31, impact factor: 4.520)

Key Funding

Burnham and **Haas**, (1998 – 2002), £43k funding from University Hospitals Coventry and Warwickshire to develop practical clinical implementation of intensity modulated radiation therapy.

Burnham and **Haas**, (1999-2002), £50k funding for EPSRC Case studentship in collaboration with Park Medical Ltd and UHCW to develop medical image analysis incorporating knowledge and feedback.**Burnham** and **Haas**, (2002-04), £90k Elekta Ltd TCS/KTP 3787, (awarded GRADE 1 and KTP Prize in 2005) to model patient support system and design of new control system for the development of dynamic therapy.

Burnham and **Haas**, (2002-2005), £54k funding from Industrial Case EPSRC Training Award no. 02303507 to Research into the use of plastic to develop new compensating devices to modulate radiotherapy treatment beams

Haas and **Burnham** (2005 - 2009) with 25 partners €7M MAESTRO EU project (FP6/CE/LSHC/CT/2004/503564). Funding to Coventry University €394k to develop work package 1 and adaptive radiation delivery tracking and control for radiotherapy.

4. Details of the impact

Haas and **Burnham**'s research has underpinned the development of equipment which delivers treatments for rare skin cancers and optimises the targeting of treatments to kill cancer cells within the body by minimising collateral damage to healthy cells caused by the breathing of the patient during treatment. In addition, **Haas** has created a phantom and associated evaluation methodologies which have been used to validate the potential for the use of control methodologies to focus the targeting of radiotherapy treatment in commercially available clinical systems.

Health impacts and impact on clinical technologies

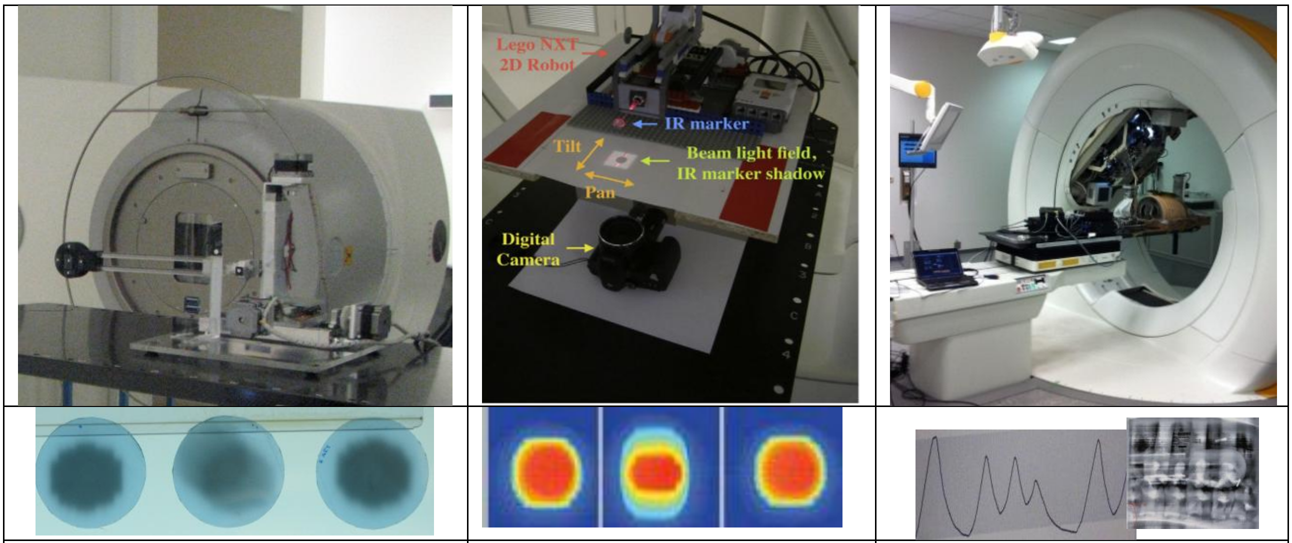
The health and clinical technologies impacts stem from research to develop and evaluate the clinical use of control theory and its application to develop niche cancer treatment machines.

The Total Skin Electron Betatron Unit (TSEBU), was jointly developed by Coventry University and the University Hospital Coventry and Warwickshire (UHCW), between 1997 and 2004 has treated with positive clinical outcomes 29 (including 15 between 2008 and 2013) patients suffering from rare forms of skin cancer such as Mycosis Fungoides or Sezary syndrome. **Haas** and **Burnham** provided a vital contribution to the TSEBU design and with their student implemented the control system on an industrial controller. The device proved effective and the initial simulation study led to the current clinical machine. Adrian Wilson, Director of Clinical Physics, University Hospitals Coventry and Warwickshire stated *'Undoubtedly the Coventry* TSEBU *facility has been a great success to many patients in the UK … the impact of the treatment on the patient is phenomenal' … a great success to many patients in the UK.´* Coventry University '*turned it from an idea to something that was real, it has created a unique device* … a *tool in our armoury*' [a].

The anthropomorphic thorax phantom was designed jointly with UHCW and its control system implemented by **Haas**, PhD and MRes students under joint supervision with UHCW was one of the first applications of LabVIEW to control a 4 axis medical device using low cost hardware. The research "demonstrated that one can produce an anatomically accurate phantom with anatomically realistic movements to help quantify advantages and disadvantages of different approaches to delivering radiotherapy". The phantom was used extensively during the evaluation of the couch motion compensation system developed during the MAESTRO project.

"Elekta decided to work with Coventry University to improve our knowledge of control systems, and to apply additional academic know-how to our development. Following the KTP, the Synergy product was released onto to the radiotherapy market with widespread acclaim." John Allen, Chief Engineer, Oncology Systems Technology, Elekta [b]. The model predictive control system implemented on the Elekta Precise Table™ demonstrated that this particular idea was feasible. The original TCS/KTP with Coventry University had a positive influence on the future direction of Elekta's business. The former TCS/KTP associate supervised by **Haas** has become an expert in the control systems part of Elekta's product and a key player in the development of the *Agility* multileaf collimator, a new cancer treatment product which '*enables significantly faster and more precise target-guided treatment for patients'* Kevin Brown, Global VP Scientific Research, Elekta [c].

The research expertise gained through the MAESTRO project led UZ Brussels to ask **Haas** to advise on methods to evaluate the tracking ability of the VERO from Brainlab/Mitsubishi http://www.vero-sbrt.com/ [6], see Figures 2b,c. The VERO stereotactic body radiotherapy (SBRT) is a niche cancer treatment machine that is able to deliver high dosage to the tumour thanks to its ability to track the tumour motion thereby reducing the impact of radiation on healthy tissues. Wohlgemuth (Project Manager, Brainlab) said "*Tests with the MAESTRO Phantom were performed at an early stage provided a starting point for deciding on focus of further development. These tests especially were helpful for the development of dedicated imaging procedures and implant detection for dynamic tracking*" [d]. The VERO platform characterisation experiments were published in a journal paper co-authored by staff from UZ Brussels, Brainlab and **Haas**. Wohlgemuth noted that these cited publications were used for the validation of real-time tumour tracking. This validation was required to "release tumour tracking for clinical use". Wohlgemuth added that the system has been in clinical use since 2011. Currently there are ten VERO installations worldwide with five more installations in progress. The VERO based in Brussels has treated 15 patients since 2011.



a) Motion compensation, irradiated film comparison [3-5]	b) VERO tracking [6] & video reconstructed motion	c) MAESTRO phantom with VERO (motion + x-ray)

Figure 2: Evaluating the performance of motion tracking and compensation exploited by UZ Brussels, Belgium and Brainlab, Germany to assess and subsequently deploy clinically the VERO.

Impact on practitioners and professional services stems from the introduction of control tools and research methods to radiotherapy practitioners and changed the view of commercial companies about the value of working with universities. John Mills, Radiotherapy Manager, University Hospitals Coventry and Warwickshire indicated that "**Haas** brought a broader and much more open approach to the Radiotherapy Department at the hospital which had traditionally been very academic and gave a boost to the research culture in the Hospital" [e]. Adrian Wilson highlighted that **Haas**' primary contribution in terms of changing practices within UHCW was "the introduction of a kind of 'rigour' of looking at how one can control things, putting the problem into a framework and then mathematically describing the control" [a]. Kevin Brown stated that computer simulations such as MATLAB/Simulink have increased together with the applications of control theory at Elekta and that the experience with the collaborative research project with **Haas** led to Elekta becoming more comfortable with collaborative approaches with universities.

5. Sources to corroborate the impact

a) Director of Clinical Physics, University Hospitals Coventry and Warwickshire
b) Chief Engineer, Elekta Oncology Systems Technology Limited
c) Global VP Scientific Research, Eleka Limited
d) Senior Project Manager, Brainlab AG
e) Radiotherapy Manager, University Hospitals Coventry and Warwickshire