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(R)evolutionary improvements in the design of interventional X-ray systems

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Abstract

Interventional X-ray systems are used to acquire 2D and 3D images of complex anatomical structures (e.g. the cardiovascular system). These images provide a clinician with feedback in a medical procedure, which enables advanced minimally invasive treatments. A typical interventional X-ray system contains an X-ray source and detector, connected by a C-shaped arm. Several stacked motion systems enable the C-arm and imaging equipment to move spherically around an isocentre. This allows for 2D X-ray images to be taken at various projection angles. Other imaging techniques such as 3D computed tomography are enabled by this core functionality.

Developments in interventional X-ray systems are often a compromise between performance, clinical usability, and cost. This paper presents three novel mechatronic architectures, which are designed to break through this trade-off. The proposed designs aim to improve the interventional X-ray system on multiple, application-specific levels. The first system focusses on improved image quality and clinical usability of 3D scans (high-end applications). A dual stage design allows for significantly extended and faster scanning motions, with a 55% smaller footprint in the operating room. It is based on a quasi-kinematic roll guide design, resulting in less nonlinear behaviour, and improved alignment of the imaging equipment. The second system decreases cost and installation requirements, while maintaining and adding to the current imaging capability (low-end applications). By reconsidering the degrees of freedom needed, a lightweight design is created (>50% mass reduction), with an improved stiffness to mass ratio. Both system 1 and 2 present an evolutionary improvement on existing architectures. As a revolutionary alternative, the third system pursues high-end performance and optimised workflow, at reduced overall cost. It features a compact and lightweight (~500 kg) mechatronic design which makes optimal use of the space available in the operating room. A full scale mock-up of this system has been built. Currently, a detailed design, including hardware realisation is being made for experimental performance validation at subsystem level.

Interventional X-ray systems, interventional radiology, mechatronics, light and stiff design

1. Trade-off in system development

Performance, clinical usability, and cost, are three conflicting, but key aspects in the development of interventional X-ray systems. Performance can be expressed in producing high quality 2D and 3D images, at minimal X-ray dose. This requires positioning of the imaging equipment over extensive and high speed 3D trajectories, with a reproducibility of ~0.1 mm. A system's clinical usability is largely determined by its obtrusiveness. Hereto, current system architectures comprise a series of rotational and translational joints, connected by long and slender structural elements (Figure 1). This somewhat limits the obstruction to clinicians and medical equipment. However, it also leads to a large structural mass (~1200 kg) and relatively low stiffness. The resulting structural deflections, combined with backlash from form-closed roller guidance systems, cause a (reproducible) misalignment of the X-ray beam of up to ~10 mm. This translates to an excess radiation dose of approximately 10%, and introduces a need for extensive and time consuming geometric calibration.

2. Dual stage design (system 1)

Using an interventional X-ray system to create 3D reconstructions (3D images), is proven to be an asset in an increasing number of clinical disciplines. For this application (CT), reconstruction algorithms combine multiple 2D images, taken at various angular projections. Typically, two scanning motions can be distinguished. A propeller scan (Figure 2, top) is carried out with the C-arm at the head end of the table. The large scan range (>200°) allows for the use of exact reconstruction algorithms [1], and application specific scan trajectories [2]. Both factors contribute in achieving high quality 3D images with minimal artefacts (such as streaks). A roll scan (Figure 2, bottom) is performed with the C-arm at the side of the table. This type of scan requires a smaller footprint in the operating room, and leaves valuable space at the head end of the table (e.g. for anaesthesia). However, the C-arm roll guidance has a smaller (180°) range of motion, which dictates the use of approximate reconstruction algorithms. Furthermore, backlash and other mechanical imperfections in the roll guide limit motion reproducibility. 3D images generated by the roll scan are therefore of inferior quality compared to the propeller scan, and less suited for procedures involving soft tissue imaging.

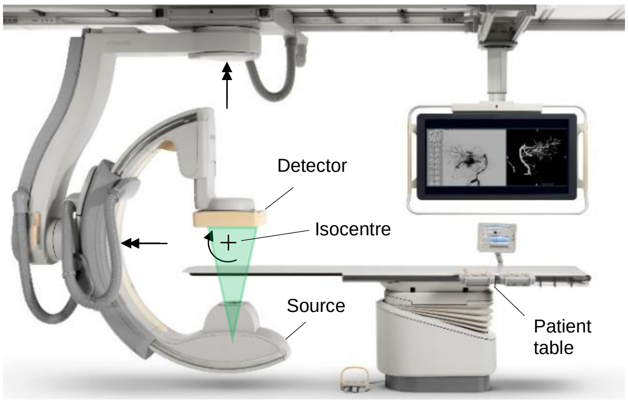

Figure 1. Typical interventional X-ray system

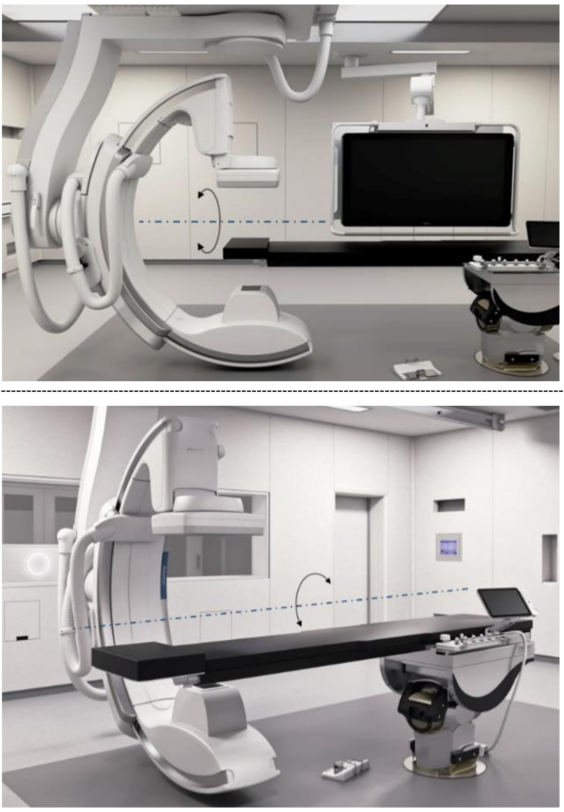

Figure 2. C-arm position for 3D propeller and roll scan (top / bottom).

System 1 aims to combine the image quality of the propeller scan, with the clinical usability of the roll scan. Its mechanical structure features an additional joint in the arm that connects the C-arm to the ceiling (Figure 3). The axis of this rotational joint coincides with the isocentre. In combination with the existing rotational joints, it hereby forms an additional spherical motion stage. This dual stage design allows for an extended ‘roll’ scan over a range of 300°, with a 55% smaller footprint compared to the propeller scan (Figure 3).

A large part of the 3D scan range is now covered by the spherical motion stage. The range of motion of the C-arm roll guidance can therefore be limited to clinically relevant 2D projections angles only (±60°). This enables the C-arm and its roll guidance to be structurally improved. A quasi-kinematic roll guide design, and elimination of backlash result in far less nonlinear behaviour and improved reproducibility.

By correctly applying closed box structures in the C-arm and roll guide, a stiff and lightweight design is created. This leads to 30% less deflection of the C-arm due to gravitational and inertial forces. The amount of excess radiation, used to guarantee full detector coverage, can therefore be decreased. Hereby, unnecessary radiation dose for both the patient and medical staff is reduced. Initial design iterations indicate that a 40% mass reduction is achievable for the C-arm and roll guidance. Similar results are expected for the complete system.

3. Novel floor-mounted base (system 2)

Typical interventional X-ray systems are able to move the C-arm in three rotational Degrees of Freedom (DoFs). Two of these DoFs (roll movement of C-arm, and propeller movement, Figure 2) are used to move the imaging equipment spherically around the patient. The third DoF (rotation around a vertical axis) is only used to position the C-arm at either side, or at the head end of the table.

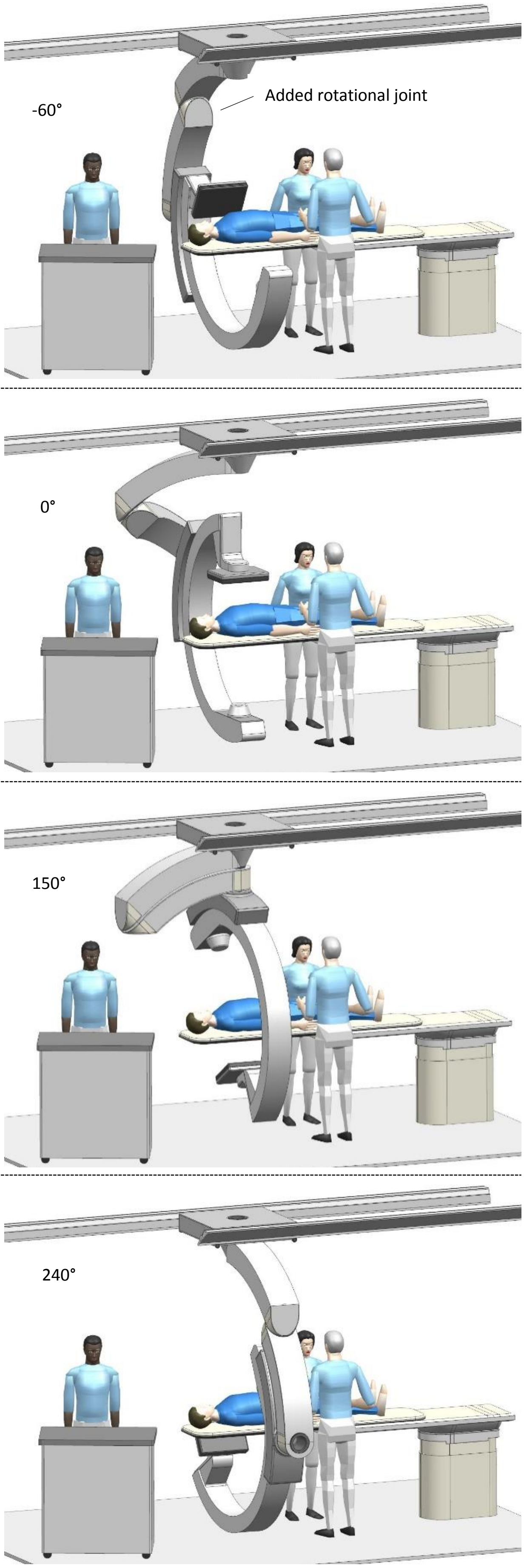

Figure 3. System 1: additional rotational joint allows for a 300° extended ‘roll’ scan (-60° to +240°).

System 2 (patent applied for) aims to decrease the system's cost and installation requirements, while maintaining and adding to the current imaging capability. Hereto, it is based on only two rotational DoFs to move the C-arm (Figure 4). The C-arm is supported by a roll guidance, which allows for a roll moment. The guidance is part of a floor-mounted base, which can rotate around a vertical axis. The propeller DoF is omitted in this design. Hereby, out-of-plane rotation of the C-arm w.r.t. the gravitational vector is prevented. This eliminates torsional deformation of the C-arm due to gravitational and inertial loads (~60% of worst case C-arm deflection). Furthermore, it enables space at the sides of the C-arm to be used for the construction of the base. This allows material to more efficiently resist the (now mainly in-plane) loads, exerted by the C-arm. Both factors reduce the misalignment of the imaging equipment, and cause it to be more constant over the range of motion. This again reduces the amount of radiation that is projected outside of the detector, and thereby decreases the dose for both patient and staff.

The absence of a propeller rotation decreases the amount of structural components, actuators, and measuring systems, compared to traditional systems (Figure 1). The cost and complexity of the system is hereby lowered. Additionally, the more efficient construction allows the system to be more lightweight (~500 kg). This reduces the cost of production, transport, and installation. It also leads to less stringent requirements for the building's structure to which the device is mounted. As such, the device can be installed at lower cost, in a greater variety of rooms (e.g. office based labs).

The two rotational DoFs allow for a similar spherical positioning of the C-arm as in the original system. Furthermore, all clinically relevant projection angles can be achieved with multiple C-arm postures (Figure 4, lower images). This allows a clinician to choose a neutral position for the system at the left or the right side, or at the head end of the table. From this neutral position, clinically relevant projection angles can be achieved by rotating the base within a 135° range (Figure 4, indicated in blue).

The C-arm roll guidance is based on the use of rolling elements, and has a range of motion of 180°. This allows for basic 3D reconstructions to be made with the C-arm at the side of the table (along the entire length of the patient). For high quality 3D reconstructions of the upper body, both rotational DoFs can be used simultaneously in a dual axis 3D scan. This scan starts at a -105° roll angle (Figure 5, left). While rotating around the vertical axis over 180°, the C-arm is moved to a near neutral roll angle, and back to -105° (Figure 5, middle and right). This results in a close to circular scan path of 210° (-105° to +105°), allowing exact reconstruction algorithms to be used ([1], minimises artefacts). In addition to the rotational DoF, the base can be made movable in longitudinal or lateral direction w.r.t. the patient table (Figure 4, black arrows). This would allow for full body imaging without having to move the patient, and easy parking of the system when not needed. To keep installation requirements to a minimum, initial designs for this translational stage include components which guide the base across the floor surface of the clinical room.

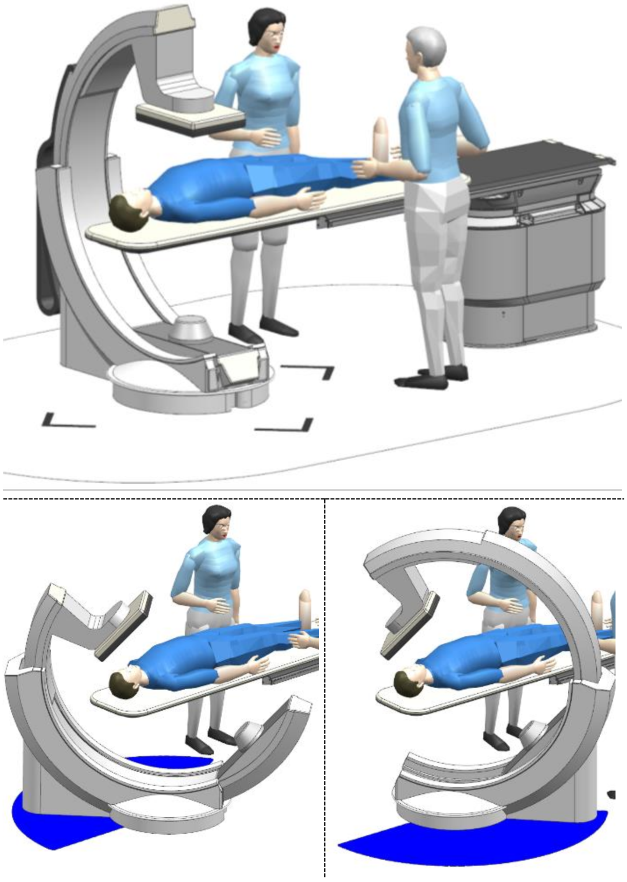

Figure 4. System 2: 2D and 3D imaging capabilities at reduced cost and installation requirements.

4. Advanced mechatronic alignment (system 3)

Both system 1 and 2 use a structural beam to physically connect and align the X-ray source and detector. Despite their slender construction, this beam, and part of the motion stages, take up valuable space around the patient table. System 3 (patent applied for) provides a revolutionary alternative (Figure 6). This system aims to optimise the clinical workflow. It features two separate mechatronic systems, which are capable of moving the X-ray source and detector in space over six DoFs. Both systems are designed to make optimal use of the space available in the operating room, and to limit obstruction to the medical

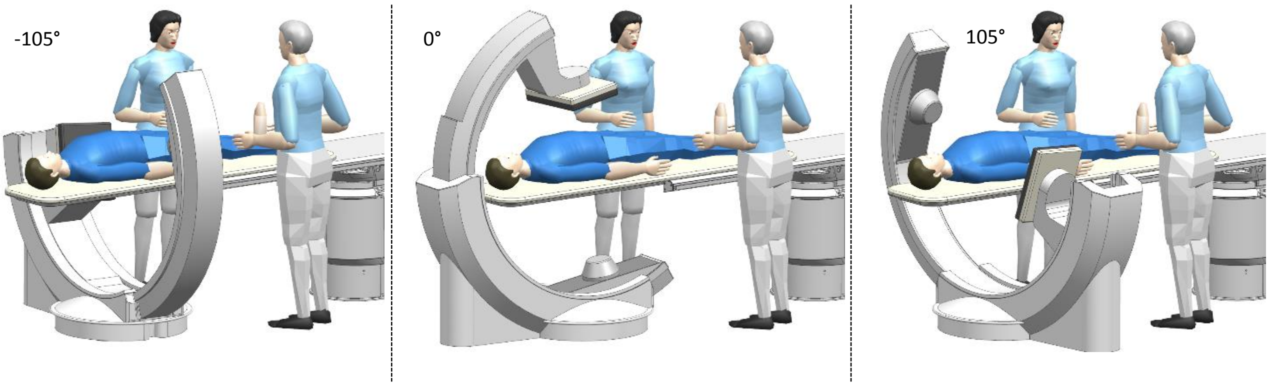

Figure 5. System 2: dual axis 3D scan, for high quality 3D images of upper body.

procedure and staff. The upper system contains a SCARA arm, which provides for three DoFs in the horizontal plane. A vertical translation module, and two rotational joints are used to couple the detector to the SCARA arm. This setup ensures that the actuated components operate either above head height (2.10 m), or directly above the detector (Figure 6). The lower system features a custom, six DoF articulated robot. It is mounted to a linear translation module beneath the patient table, creating a redundant kinematic layout. This enables system movements to be programmed such that the robot arm operates within the width of the patient table, for all projection angles (Figure 6).

Both the upper and lower system are able to move the X-ray source and detector in six DoFs. This provides for additional functionality, on top of the ability to move the imaging equipment along spherical, longitudinal, and lateral trajectories. Contrary to other systems, it enables the height of the (virtual) isocentre to be adjusted in a range of 100 mm. The clinician can therefore set the patient table to an ergonomic working height, and adjust the isocentre position accordingly. Furthermore, quasi-static deflections in the mechanical structure can be compensated for. This enables the misalignment of the X-ray beam on the detector, and thereby the unnecessary radiation dose to be minimised. Hereby, we aim to reduce the misalignment of the X-ray beam from ~10 mm to ~1 mm. A model-based, calibration-based, or image-based approach [3] could be explored to quantify the actual misalignment prior to, or during operation.

If system 3 is (temporarily) not needed, its flexible setup allows it to be parked easily. Hereto, the lower system folds to its neutral position beneath the patient table. The SCARA arm in the upper system can be used to move the detector and motion stages away from the patient table. If laminar air flow equipment is present, the mounting point of the upper system can be located outside of the sterile field.

By using two separate systems, the payload (imaging equipment) is coupled to the nearest fixed world (detector to ceiling, X-ray source to floor). This shortens the force path, and thus the amount of material required to carry the payload. Furthermore, currently available imaging equipment has decreased in mass, compared to components used in the past. Both factors contribute to a significant reduction in system mass (total mass ~500 kg), and therefore in the cost of transport and installation. Apart from that, the six DoF motion capability allows for the patient table (currently comprising seven DoFs) to be simplified. Considering the total clinical setup, system 3 is therefore expected to enable a significant integral cost reduction.

5. Summary

This paper presents three novel mechatronic architectures, designed to improve the interventional X-ray system in terms of performance, usability, and cost. System 1 focusses on improved image quality and clinical usability of 3D scans (high-end applications). A dual stage design allows for scanning motions up to 300°, with a 55% smaller footprint in the operating room. It is based on a quasi-kinematic roll guide design, resulting in less nonlinear behaviour, and improved alignment of the imaging equipment. System 2 decreases cost and installation requirements, while maintaining and adding to the current imaging capability (low-end applications). By reconsidering the degrees of freedom needed, a lightweight design is created (>50% mass reduction), with an improved stiffness to mass ratio. The third, and most revolutionary system pursues high-end performance and optimised workflow, at reduced overall cost. It features a compact and lightweight (~500 kg) mechatronic design which makes optimal use of the space available in the operating room.

6. Outlook

A full scale mock-up of the third system is built, which is used to demonstrate workflow related advantages to several stakeholders. Currently, a detailed design and analysis of the expected performance of system 3 is being made. Initial estimates indicate that a control bandwidth of at least 10 Hz can be achieved using conventional non-collocated PID control, allowing for a factor 5 improvement in positioning performance. In the upcoming months, various critical subsystems will be realised for experimental validation of these performance characteristics.

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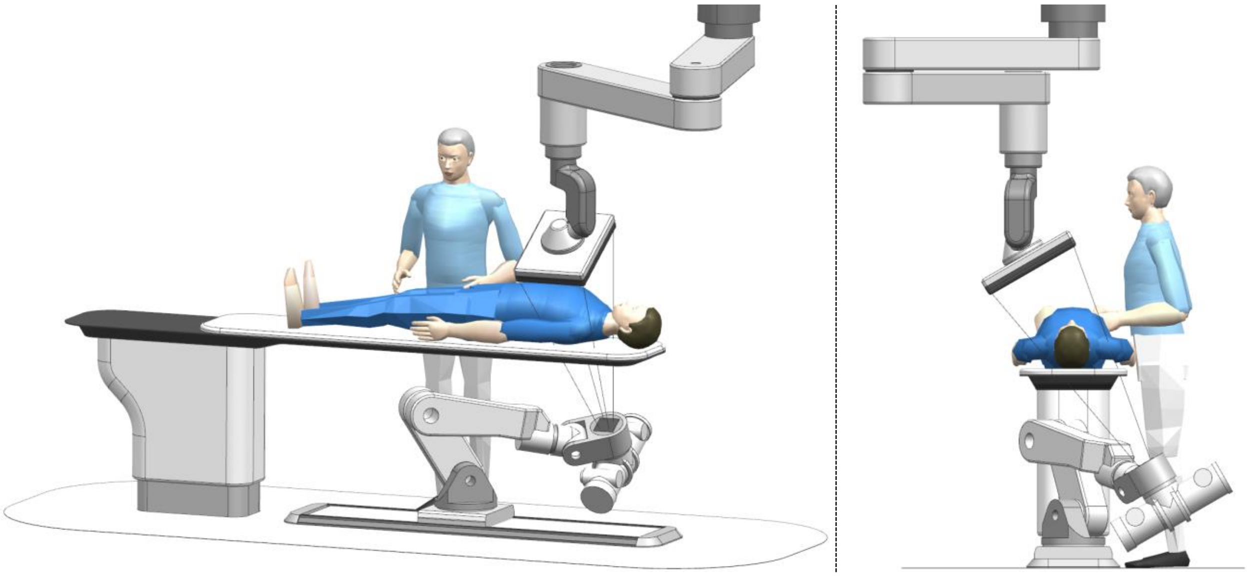

Figure 6. System 3: two separate mechatronic systems to move the X-ray source and detector. Upper system operates above 2.10 m, lower system moves within contours of table.