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Adaptive Collision Avoidance System for Contemporary Therapy Suites

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Abstract

Adaptive Collision Avoidance System for Contemporary Therapy Suites

A contemporary therapy suite is a collaborative working space, where image-guided surgery and intervention procedures are carried out. It refers to operating rooms, intervention rooms, and hybrid operating rooms together. The suite is densely populated with people and devices during the treatment of a patient. It is dynamic by its nature; people and devices are required to move for accomplishing their tasks.

Movement of a device or object in the dynamic and populated environment introduces safety threats. The devices are stand-alone and unaware of their vicinity; therefore, they can collide with surrounding people and devices. Such collisions can cause not only injury to people or economic damage but also can interrupt the treatment.

The purpose of this work is to introduce an adaptive and comprehensive collision avoidance system for the contemporary therapy suite, which ensures safety of people and devices without restricting the agile essence of the procedures.

A comprehensive and generic collision avoidance system for therapy suites has not been found in the literature. This work investigates components, observes their mutual interactions during procedures, analyzes the dynamics of the suite, and derives requirements for the collision avoidance system. No evaluation methodology has been reported in the literature which could assess the performance of the system, therefore describing performance evaluation criteria is part of this work. It implements a solution, based on the real-time swept volume and distance computation for self-collision detection method by Täubig, Bäuml, and Frese. The work extends this solution in order to represent the components of the therapy suite, take clinical requirements into account, distinguish between the cooperative and destructive interactions between components, identify safety threats, and act to prevent collisions between components.

The implemented solution is evaluated in an experimental intervention room. The experiments show that the solution adapts to instantaneous velocity, use-case, and update-rate of the components. It distinguishes the desired and undesired proximities of components, avoids all undesired interactions between components, and achieves human comfort.

The collision avoidance system ensures safety and human comfort while improving agility in the contemporary suite. The implemented solution is generic so that it can be extended to further and future components and interactions.

Contents

1

Introduction

Recent technological developments are rapidly embedded in the medical fields, altering the practice of operations and interventions. Evolving clinical needs, together with the introduction of new devices and equipment, necessitates a collision avoidance system to ensure the safety of the clinical performance and the workflows. This chapter gives an overview of the evolving perspectives on the therapy suites, referring to the interventional suites and the operating rooms together. Ongoing studies on integrating the devices in the environment with each other towards automating a clear clinical task are briefly described. The rising need for a comprehensive collision avoidance, which ensures safety and agility in the future's therapy suites, is clarified.

1.1 Contemporary Therapy Suites

The therapy suite of the future has been envisioned to have pre-procedural planning opportunities, integrated intra-procedural information sources and comprehensive imaging capabilities, and advanced visualization techniques [1]. Hybrid operating rooms (ORs) are the embodiment of the next-generation therapy suite today: They bring the devices and advantages of conventional ORs and intervention rooms together and they are used by multiple disciplines and a wide range of purposes. Contemporary therapy suite in this work refers to ORs, intervention rooms, and hybrid ORs together. The work introduces a collision avoidance system for contemporary therapy suites, which serves the safety requirements of modern ORs, intervention rooms, and hybrid ORs.

Bringing interventional and surgical techniques in the hybrid OR requires a compilation of all associated equipment in the same physical environment. Intervention-specific and surgery-specific equipment can be found together in the same hybrid OR. C-arm computed tomography devices, for instance, play a vital role in providing cross-sectional three-dimensional (3D) intra-procedural images in the hybrid OR, which were not found in the conventional ORs [2]. As a result, the hybrid ORs are more crowded than the conventional ORs and intervention rooms.

Robotic technologies are being adapted to medical use, leading to the development and improvement of computer-assisted surgery and intervention performances. Robots have been introduced to the set of essential devices of modern intervention rooms and ORs in the meantime. A robot is a self-powered and computer-controlled device, assisting the interaction between the team and the patient throughout the procedure in achieving complex tasks [3]. They improve the precision and steadiness of surgical instruments, scaled movements, telemanipulation, and tremor elimination. They make treatment processes less invasive and increase the patient and medical staff comfort [4]. Initial studies report that robotic surgery has improved patient outcome compared to the conventional techniques, utilization of robots in more treatments is expected [5], [6].

1.2 Problem Description

Imaging devices and assistant robots are not the only equipment in a therapy suite. Other integral elements in the environment include, but are not limited to, patient tables and associated accessories, insufflators, anesthesia devices, large-displays, and supplementary monitors, surgical instruments, powered injectors, navigation systems, surgical lamps, and other ceiling-mounted equipment. Throughout the context of this study, every single physical object, including the devices, tools, instruments, and human beings, located in a therapy suite, is referred to as a component.

While surgeries and interventions evolve and become more sophisticated, additional components and technologies are introduced to the therapy suites. Although therapy suites are already overcrowded and dynamic spots, they get more dynamic and populated with increased hazards [7]: Stationary and moving components, which are in general stand-alone and uncooperative; unaware of each other, the patient, the team, and the surrounding [8]. The lack of awareness between the components results in safety and effectiveness gaps [7].

The medical staff is responsible for performing the procedural tasks and utilizing the equipment. Manipulating therapeutic components requires close attention of the staff members as getting the right action at the right time and the right place is crucial for the clinical outcome. On the contrary, time pressure, stress, fatigue, the inexperience of a staff member can lead to improvidence, resulting in obtrusive interactions with other staff members as well as equipment [9]. Collisions, any obtrusive physical interactions between any components in the environment, might damage patient and staff members, devices, and instruments. Therefore, they introduce safety threats and must be avoided [10].

1.3 The Purpose and Contribution of the Work

The purpose of this scientific work is to conceptualize and implement a comprehensive real-time collision avoidance system for contemporary therapy suites. Being real-time means that undesired proximities between components can be detected and proper actions to prevent the potential collision can be taken before a collision occurs. Being comprehensive implies that the solution shall not be specific for certain components; it shall be generic so that it can be applied to any component of interest. The work aims at ensuring the safety of the components without interfering with the procedural workflow nor compromising the agility of the processes and human comfort.

For a relatively long time, collision avoidance concepts have been investigated in different areas, such as aerial and maritime navigation, robotic applications, and autonomous driving. These concepts cannot be applied to the therapy suites due to a lack of a clear understanding of the collision avoidance requirements in the therapy suites. Furthermore, people and devices collaborate in close proximity around the patient without physical safeguards to treat the patient. Compared to the collision avoidance solutions in other fields, the patient-centric situation in the therapy suite is unique.

Some methods for collision avoidance have already been implemented in the interventional and surgical environments. But these methods are not comprehensive, they concentrate only on a pair of devices and ignore the rest of the room. Therefore, the existing collision avoidance concepts cannot address the problems of the therapy suites.

This work introduces an adaptive collision avoidance system, which has been customized specifically for the therapy suite. It investigates all components of the therapy suites as well as their interactions from a collision perspective, analyzes the physical constraints and associated risks, classifies components and their interactions, and clarifies the functional and quality requirements. Clinical requirements from such a system are identified in order to ensure compliance with the procedural workflows. A methodology for evaluating the performance of such a system is not found in the literature, introducing performance indicators for the collision avoidance system is part of the work. The proposed system is implemented and experimentally evaluated in a laboratory setting. The implemented solution is adaptive so that it ensures safety in the therapy suite without comprising the agility of the procedure. The solution is comprehensive, it is not restricted to a certain set of components.

Chapter 2 provides an analysis of the typical components and processes in therapy suites. Based on this analysis, the scope of the collision avoidance system is defined, the functional and quality requirements are identified, and the performance evaluation criteria are introduced. Chapter 3 gives an overview of state of the art, with a closer look at studies of collision avoidance at robotic and clinical environments. Afterwards, a review of the patent situation in the related area follows. Chapter 4 explains the solution approach and the system architecture, including the details of the processes handled by the functional units. Chapter 5 deals about the evaluation of the proposed system in the experimental setup. Discussions and future perspectives of the work are given in Chapter 6, while in Chapter 7 conclusions are drawn.

2

Requirements Analysis

This chapter starts with the investigation of the dynamics of the environment; it reduces the complexity of the collision avoidance tasks by categorizing the components, analyzes their mutual interactions, and classifies collisions with respect to their impact. Based on the practical needs of the team members within the therapy suite, functional and quality requirements of the collision avoidance system are described. The chapter concludes with evaluation the criteria for the performance of the collision avoidance system.

2.1 Investigation of the Environment

Prior to scoping the requirements, it is essential to constitute necessary information about the components in a therapy suite as well as their characteristics in terms of collision. For characterizing a consistent solution, it is critical to understand under which circumstances the collisions occur, the severity and probability of certain collisions. This section illuminates the entities and their interactions in a therapy suite. All of this is mandatory for defining requirements and performance evaluation criteria.

2.1.1 Components in the Therapy Suite

Every physical entity inside a therapy suite is considered as a component, consisting of one or more bodies and having a risk of colliding to or being collided by another component throughout the entire span of a procedure. With an increasing variety of treatments and necessary specialized equipment, the list of components, which can be found in a therapy suite, can be boundless. For bringing the complexity to a manageable level, major criteria are autonomy, self-quantification, and electronic manipulability.

Autonomy of a component is the ability to freely make movement decisions and executing those actions without the need for external support. Human beings are the only autonomous components in the therapy suite, who make decisions on their own and require no external forces for executing the decision. Nevertheless, not always all humans act autonomously: Patient can have special conditions, for instance, being sedated, resulting in limited or no autonomy in contrast to the staff. Furthermore, the patient body is fixed on the table, that means movements of the patient body are directly coupled to table movements.

The staff does not only carry on their own movements, they are also responsible for and capable of manipulating the nonautonomous components according to the context of the procedure. Nonautonomous components can be subcategorized based on how they are manipulated.

- Components, which are not autonomous but still can be electronically manipulated, are so-called active components; their positions or postures can be altered without any external force. The angiography system, patient table, and assistant robot are essential members of this category. With the advancement of image-guided therapies, sliding computed tomography and magnetic resonance scanner, and linear accelerator emerged in the contemporary therapy suites, which belong to this category as well. The nonautonomous active components receive motion commands from the staff members via software and hardware interfaces, relocate or change their postures themselves in response without additional human intervention.
- In contrast, a wide variety of nonautonomous components exist, which are passive; relocating or changing their postures is based on an external force. Nonautonomous passive components constitute the most populated category within the therapy suite; however, the members of this category can still have different characteristics. Therefore, subcategorization has been made based on where they reside within the therapy suite:

  - Ultrasound device, laparoscopic and endoscopic visualization systems, anesthesia machine, handheld surgical and interventional instruments are mainly found on trolleys, and they commute within the hospital between separate therapy suites. Those components are often spontaneously needed during a treatment, which causes additional traffic within the therapy suite.
  - Not all passive nonautonomous components are located on the floor: Navigation systems, supplementary monitors, power and gas stations, X-ray shields, and surgical lights are typically mounted to the ceiling. These ceiling-mounted components are found at an altitude different than the trolley-based components, resulting in different levels of collision severities and frequencies.

Self-quantification of a component is the ability to digitize its own joint values, hence being self-aware of the posture. Some components in the therapy suite, such as the advanced imaging modalities, patient table, and assistant robot, are self-aware of their postures. They are equipped with sensors to measure and quantify their joint values, which afterwards can be communicated with the external world. In contrast, majority of the components within the therapy suite cannot quantify their postures nor locations digitally. Quantification of their positions and postures, as well as communication of digital values with third party entities, necessitates external means of observation. Investigation and classification of components from a self-quantification perspective is essential to design appropriate methods for data acquisition and component representation.

Table 2-1 summarizes the most prominent components of the contemporary therapy suites in their classified categories. This categorization is utilized to characterize the proper data acquisition, communication, and perception methods as well as for clarification of collision avoidance strategies for the different categories of components. External quantification modalities are required to digitize the location and posture of the components, which are not self-quantifying. Electronically manipulatable components can be intervened by the collision avoidance system to trigger and retain their motions.

	Autonomous	**Nonautonomous**		
		Active	Passive	
			Trolley-based	Ceiling-mounted
Self-quantifying	None	• Angiography system • Patient table • Computed tomography scanner • Assistant robot • Linear accelerator • Magnetic resonance scanner	None	None
Not self-quantifying	• Patient • Staff members	None	• Patient • Ultrasound device • Laparoscopic and endoscopic visualization systems • Anesthesia machine • Power injector • Diagnostic and therapeutic instruments	• Navigation systems • Supplementary monitors • X-ray protection shields • Surgical lights • Power and gas stations

Table 2-1: Classification of typical components in a therapy suite

Instead of a customized solution for today's components, the study proposes a generic solution that is extensible and can be applied to future components. From this perspective, embodying the specific components into generic components is beneficial in order to generalize the solution and to respond to the future needs within the therapy suite. To cope with the complexity of the components as well as their interactions, generic components are described based on the similar characteristics for collisions. The generic components in the therapy suite are:

- C-arm: The angiography system, computed tomography scanner, magnetic resonance scanner, and linear accelerator are advanced imaging modalities, which can be found in the therapy suites, and which have electronic-manipulability and self-quantification in common. Among them, the angiography system is significantly dominant in terms of availability, it is more dynamic compared to the others, and it can represent the other advanced devices in terms of collision characteristics. Therefore, the C-arm selected as the generic component, embodying the advanced imaging modalities.

- Assistant robot: It demands dedicated administration, which is different than other electronically manipulatable and self-quantifying components. Assistant robots are smaller in size, they may carry cutting tools, thereby get in contact with the patient body. In addition, they are typically in close neighborhood of the staff. Therefore, the impact of a collision can be different than the impact of advanced imaging systems.
- Patient table: Similar to the assistant robot, the patient table is a distinguished electronically manipulatable and self-quantifying component; it is separately treated since it carries the patient.
- Staff member: All different roles of humans, who can be found in a therapy suite such as interventionalist, anesthetist, nurse, and technician are embodied as staff members. They all act autonomously, and they cannot digitally quantify nor communicate their locations and postures.
- Patient: The patient is administered as a particular human in the therapy suite as he/she may not always be autonomous, conscious, and responsible for his/her own movements.
- Trolley-based component: This generic component embodies all passive and not self-quantifying components found on the floor.
- Ceiling-mounted component: This generic component comprises all passive and not self-quantifying components attached to the ceiling. Trolley-based and ceiling-mounted components are separately administered as they are subject to different types of interactions, and the impact of a collision can be different.

2.1.2 Physical Interactions between Components

Treatments within therapy suites are observed during interventional neuroradiology, interventional radiology, interventional cardiology, and surgery cases to figure out the occurrence probabilities and the severity of damage in case of collisions between different components. Observations are discussed and validated with two interventional radiologists and a surgeon.

The therapy suite is a collaborative space where staff members utilize devices to perform a distinct clinical task for treating the patient. Not only the members of the staff cooperate with each other, but also robots help them to carry out specific tasks. Human-beings and the robots share the same workspace, and there are no physical safeguards in between; they get into proximity, or even direct physical contact with each other. Instruments can be held by a human as well as attached to the end-effector of a robot; they contact the patient or even be inserted into the patient's body. Therefore, not all close proximities between the components shall be considered as a safety risk in the therapy suite: The proximity, even contact, of two components may be desired at a specific step of the treatment; therefore, prevention of this desired proximity can interfere with the clinical workflow. During the procedure, the components get into different use-cases in order to carry out their tasks. The desired and undesired proximities between specific components depend on their actual use-cases during the proximity.

Physical interactions between components in a therapy suite are not always collaborative; they can also be destructive. A component can physically damage the opponent or interfere with the workflow as a result. For instance, a person can be injured by an assistant robot or a monitor can be broken by a C-arm as a result of physical interaction. The result of a destructive interaction is not necessarily physical damage; it can also result in disarrangement of the equipment setup or disruption of the clinical workflow. The proposed solution shall discriminate between desired and undesired proximities, distinguish and prevent destructive interactions, namely collisions.

Collision in a therapy suite does not necessarily occur only during the procedure: There is high traffic of components into and out of the environment right before and after the procedure. The traffic is further condensed around the patient table. Tiredness, stress, and incaution of the staff, especially after the procedure, increases the probability of collisions. Hence, all types of interactions of components shall be analyzed before, during, and after the treatment.

Considering the movement characteristics of the components and the dynamic nature of the therapy suite, components can concurrently move. Furthermore, the movement of a component does not always depend on another component as well as the movement path of a component is not always known to the surrounding components and the collision avoidance system. Therefore, the proposed system shall allow concurrent and independent movements of the components, shall assume dynamic obstacles.

The collision avoidance system in this work is reactive. The components can freely navigate to any position within the environment and they are not expected to report their movement path or target position to the system. Therefore, the solution shall require no *a priori* trajectory information. The system shall monitor the use-cases of the components and allow certain proximities and contact of their proper bodies when the interaction is desired.

2.1.3 Collisions between the Components

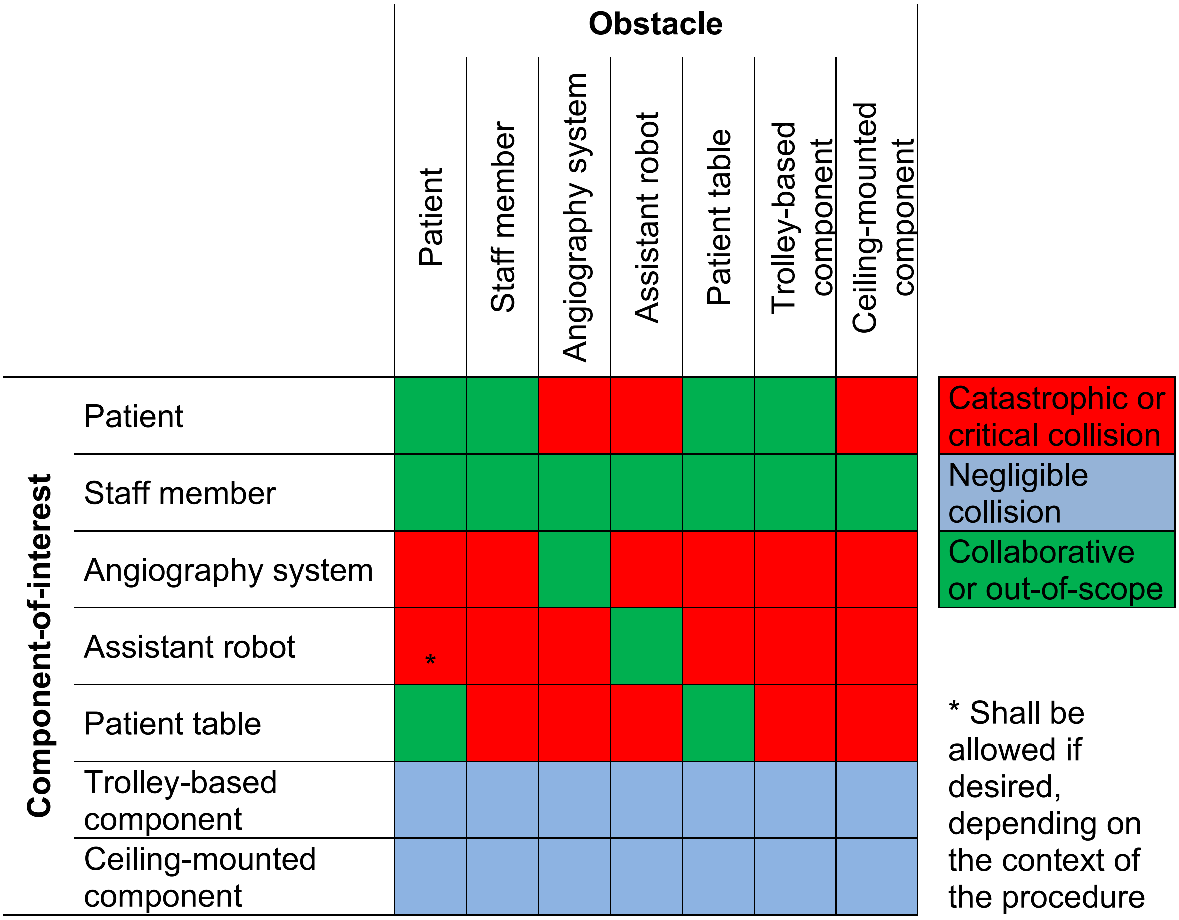
In the clinical composition, each component has the possibility to hit another component as well as being hit by another component in the neighborhood. The colliding component is referred to as the *component-of-interest*, while the collided component is referred to as the *obstacle*. The interaction between two specific components shall be analyzed from both perspectives.

Observing the environment in radiology interventions, cardiology interventions, and surgical procedures, followed by discussions with 2 interventional radiologists and a surgeon, collisions between components in a therapy suite are analyzed with respect to their impact. A collision has a catastrophic impact if it causes harm to a human being or destroys a device so that the procedure cannot resume. The impact of a collision is critical if the collision results in a damage of a device, causing economic loss, while the procedure can resume by a temporary solution. A collision has a negligible impact if it does not harm any human or device; thus, the procedure resumes after a short interference. Interactions of the generic components in the therapy suite with their surroundings are analyzed from a component-of-interest and obstacle perspective:

- Staff members have the ultimate control over the environment. Each staff member has the ultimate freedom to get in close proximity with another member and other components. As they are not electronically manipulatable, the system cannot prevent them to get in contact with another component. However, the staff members can unintentionally be collided by another component, a situation which shall be avoided. Therefore, the proposed collision avoidance system considers the staff members only as obstacles; the system is not responsible for preventing the staff members from colliding, but it is responsible for preventing collisions in which staff members can be collided.

- From an interactions point of view, a patient is different from the staff. The patient is basically a passive component attached to the top of the electronically manipulatable patient table. Table movements can lead to an unintentional collision by hitting the patient to surrounding components. On the other hand, the entire procedure is set-up in a patient-centric manner, that means all components work in close neighborhood of the patient. Some interactions are desired, they shall be allowed, while the undesired proximities shall be prevented. The patient does not by himself/herself cause critical collisions but colliding to the patient may lead to catastrophic or critical results.
- C-arms and assistant robots are special active components in the therapy suite. They have the potential to precipitate significant damage to the obstacles, resulting in a catastrophic impact on the treatment. As the assistant robot might hold incisive tools, colliding with the assistant robot can also have catastrophic or critical impact.
- Nonautonomous passive components can lead to collisions with negligible impact. Nevertheless, they are under the risk of being damaged by an active component.

The mutual interactions between individual generic components are tabulated in Table 2-2. Destructive and collaborative interactions are highlighted. The functional requirements of the collision avoidance system are later derived with respect to classes of interactions.



		Obstacle						
		Patient	Staff member	Angiography system	Assistant robot	Patient table	Trolley-based component	Ceiling-mounted component
Component-of-interest	Patient	🟩	🟩	🟥	🟥	🟩	🟩	🟥
	Staff member	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Angiography system	🟥	🟥	🟩	🟥	🟥	🟥	🟥
	Assistant robot	🟥 *	🟥	🟥	🟩	🟥	🟥	🟥
	Patient table	🟩	🟥	🟥	🟥	🟩	🟥	🟥
	Trolley-based component	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Ceiling-mounted component	🟦	🟦	🟦	🟦	🟦	🟦	🟦

🟥 Catastrophic or critical collision
🟦 Negligible collision
🟩 Collaborative or out-of-scope

* Shall be allowed if desired, depending on the context of the procedure

Table 2-2: Classification of the interactions between components

2.2 Separation of the Components

This study proposes a comprehensive collision avoidance approach for the therapy suites to address their safety, agility, and comfort needs. The solution is not based on collision detection; it prevents the collisions before they occur. Rather than perceiving the environment from the perspective of a specific component, it has a global awareness on the devices and people as well as the context and the processes.

Fundamentally, collision avoidance ensures a separation distance between components: Two components can freely move as long as the separation between them is more than a critical distance. The volume around a component, traced with its separation distance, is its separation zone. The collision avoidance system enters an alert state if another component violates the separation zone of a component. Two components are *in conflict* when their individual separation zones are overlapping. Safety measures shall be taken to resolve conflicts and prevent collisions before they occur.

In the light of the component characteristics and the dynamics of the therapy suite, the critical threshold of a separation distance depends on the characteristics of the conflicting components and the context of the procedure. This section reveals these characteristic constraints and analyzes their influences on the critical separation distances. It classifies conflicts between different component categories and explains proper actions for conflict resolution.

2.2.1 Need for Safety and Agility in the Therapy Suites

The clinical trend is toward the provision of a better quality of diagnosis and treatment at the cost of less duration of the performance. This situation stipulates the safety of the components and the agility of the procedures at the same time: The collision avoidance system must ensure the safety of components without destroying the agility of processes. Considering the high demand for efficient utilization of physical and human resources, safety must not be improved while penalizing treatment time.

Knowing that a component consists of one or multiple bodies, d_{det} denotes the separation distance between the closest bodies b_j^m and b_k^n of two separate components C^m and C^n, respectively, at the instance of conflict detection:

- Safety need of the therapy suite requires larger d_{det} in order to ensure that the conflict can be resolved before the collision occurs. Larger d_{det} improves safety.
- On the contrary, larger values of d_{det} interfere more with the movements of the surrounding components. A collision avoidance approach, which identifies all proximities of components as safety threats, is overactive; it cannot be accepted in the therapy suite. Agility need of the therapy suite requires smaller d_{det} to ensure continuous movements of the components.

Figure 2-1 illustrates the bodies b_j^m and b_k^n of the components C^m and C^n, respectively, at the instant of conflict detection: At least one of the bodies moves in the direction of the dashed line; therefore, the bodies are approaching each other. The shortest distance between the bodies at this instant d_{det} is depicted. The proposed collision avoidance system shall minimize d_{det} while ensuring that the conflict can still be resolved, and the collision can be prevented.

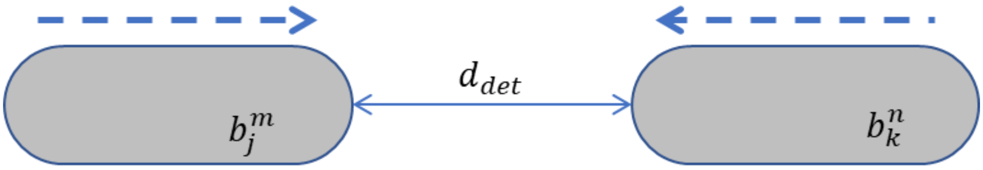


Figure 2-1: Two approaching bodies and the critical distance $\boldsymbol{d_{det}}$ between them at the instance of conflict detection

2.2.2 Need for Human Comfort in the Therapy Suites

The proposed collision avoidance system shall ensure human comfort throughout the interactions between bodies. The system must enhance the operation of electronically manipulated components so that they acceptably approach other components, without causing any stress on the staff members.

Human beings prefer to sustain a comfort zone around the self-body; presence or penetration of another component in this zone causes stress. Furthermore, the operator prefers that components do not stand intimately. A minimum separation distance around a body shall remain as penetration of another component into this zone violates human comfort. The separation distance d_{final} between the closest bodies b_j^m and b_k^n of the two conflicting components C^m and C^n, respectively, at the end of the conflict resolution shall be larger than or equal to the summation of minimum comfort distances of the conflicting bodies for the sake of the operator's comfort:

$$d_{min} = (d_{minCom}^{j} + d_{minCom}^{k}) \leq d_{final} \qquad \textbf{Equation 2-1}$$

where d_{minCom}^{j} and d_{minCom}^{k} are the human-defined minimum allowed comfort distances of the conflicting bodies b_j^m and b_k^n, respectively. In other words, the final distance between the conflicting bodies cannot be less than the minimum allowed separation between the two bodies, d_{min}.

Figure 2-2 illustrates the bodies b_j^m and b_k^n at the end of the conflict resolution: Both bodies are stationary, the collision is prevented. The actual distance between the bodies at the end of conflict resolution d_{final} is depicted.

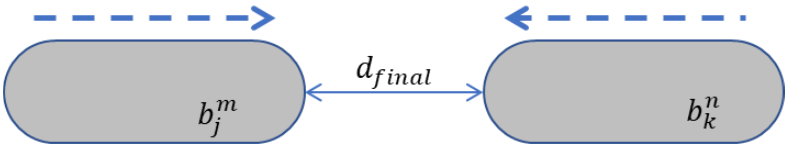


Figure 2-2: Two stationary bodies at the end of conflict resolution and the final distance $\boldsymbol{d_{final}}$ between them

A collision avoidance system is perceived as being overreacting if it detects conflict and enters an alert mode even if the components are too far apart from each other and no collision can occur. Such an overreacting system discontents the staff members and disturbs agility. Thus, the system shall not detect proximities above a certain threshold as conflicts, namely the maximum comfort distance, but still shall be able to avoid collisions. The separation distance between the closest bodies of two conflicting components at the instance of the conflict detection, d_{det}, shall be smaller than or equal to the summation of maximum comfort distances of the bodies, d_{max}, for the sake of the operator's comfort and procedure's agility:

$$d_{det} \leq \left(d^{j}_{maxCom} + d^{k}_{maxCom}\right) = d_{max} \qquad \textbf{Equation 2-2}$$

where d^{j}_{maxCom} and d^{k}_{maxCom} are the human-defined maximum comfort distances of the bodies b_j^m and b_k^n, respectively. In other words, the system is not allowed to identify any conflict between two bodies if the distance between the bodies is more than a certain threshold d_{max}.

Figure 2-3 illustrates the minimum and maximum allowed comfort distances around the bodies b_j^m and b_k^n.

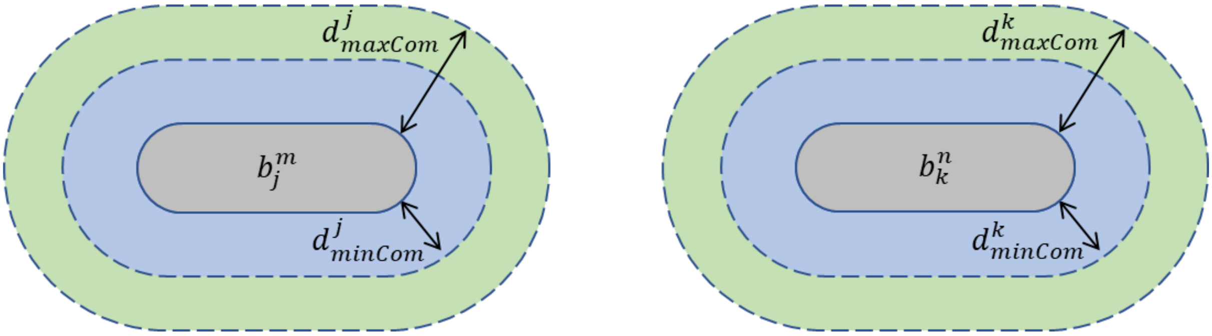


Figure 2-3: Illustration of the minimum and maximum allowed comfort distances around the bodies $\boldsymbol{b_j^m}$ and $\boldsymbol{b_k^n}$

Figure 2-4 illustrates the critical thresholds of separations between the bodies d_{max} and d_{min}. Referring to the Equation 2-2, conflict detection can only happen when the green volumes around the bodies overlap. Otherwise, the agility requirement is not satisfied. Following the proper actions and eventually conflict resolution, the blue volumes around the bodies shall not overlap, which is demanded by the Equation 2-1. Otherwise, the human comfort requirement is violated.

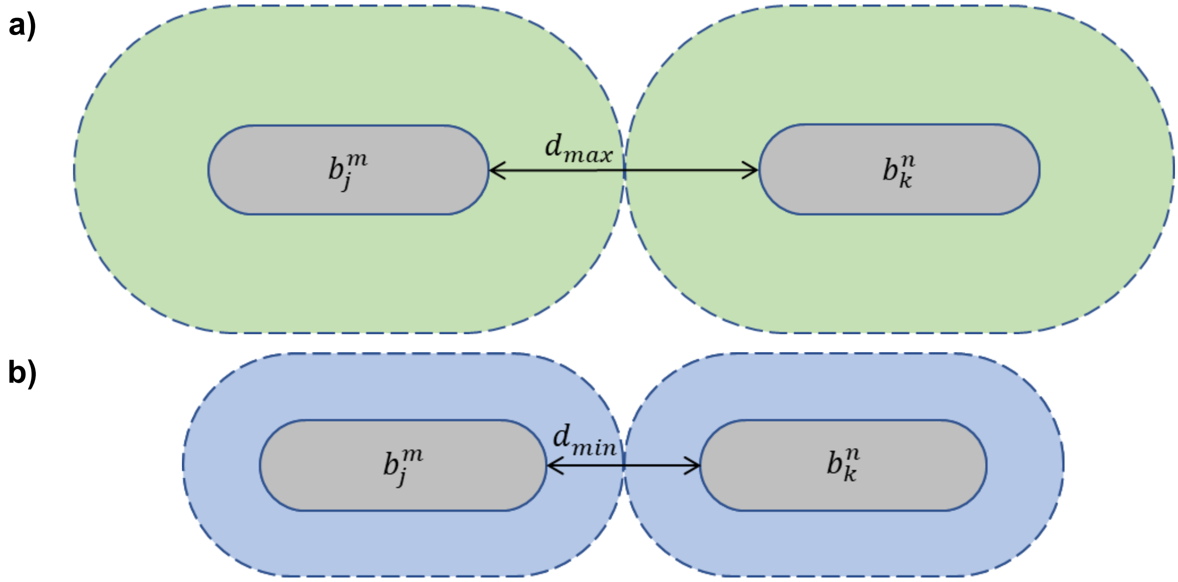


Figure 2-4: Critical thresholds of separations between the bodies $\boldsymbol{d_{max}}$ and $\boldsymbol{d_{min}}$

The distance between two approaching components, at which a human feels uncomfortable, depends on many parameters, including personality, the size of the devices, and the velocity of the approaching components [11]. This study leaves the detailed analysis of these parameters to those studies, in which the social acceptance of robots in the human-robot cooperation spaces has been investigated. In context of this study, the discomfort distance associated with a component is assumed to be the distance it can overcome in 1 second. This assumption has been made based on the experiments with the interventional radiologists: The distance between approaching components at which the staff felt uncomfortable was proportional to the instantaneous velocity of the approaching components, and it was around the 1s travel distance of the components. Therefore, the maximum allowed comfort distance of a body is equal to the maximum distance the body can travel in 1 sec:

$$d^j_{maxCom} = \frac{v^j_{max}}{1\ sec} \qquad \textbf{Equation 2-3}$$

where v_{max}^{j} is the maximum achievable velocity of the body b_j^m.

2.2.3 Adaptive Separation around a Body

There is not a global separation value, which applies to all body pairs. Each specific body pair shall be assigned a proper separation distance with respect to the component characteristics as well as the user-defined minimum comfort zones. Furthermore, the separation between a specific body pair cannot be forced to have a constant value throughout the entire procedure; it shall be adapted to comply with the safety, agility, and comfort requirements at any time point or work-step of the clinical procedure.

The instantaneous velocity of a body is proportional to its separation from the surrounding. Assuming the same update rate, the body can travel longer distance when its instantaneous velocity is higher. The system can ensure safety by assuming highest possible velocity for each body and assigning the largest corresponding separation around it. Such an assumption leads to excessive separation of the body when it moves with smaller velocity, resulting in more significant need for agility improvement. Thus, influence of the instantaneous velocity of a body to its separation distance shall be time varying.

The update rate at which position, posture, and use-case data is received from a component has a similar inverse influence on the required size of separation around the body. As the update rate decreases, larger separation of the bodies is required since a body can travel more distance until the next update information is received. On the contrary, the body can travel less distance between two succeeding update signals if the update rate is higher. The system can assume lowest update rate for each component and assign largest separation around its bodies, thereby ensure safety. Nevertheless, this method yields separation zones around the bodies larger than required and disturb the agility in return. The implemented system adapts the separation assignments to the update rates in run-time, avoids excessive separation assignment, hence improves agility within the procedure.

The close proximity of specific components during the performance of an individual task may be desired and necessary, while the same separation distance between those components can be risky at a different time of the procedure. For instance, the tip of the surgical assistant robot is usually not permitted to get closer to any component. However, the tip and the patient must get very close, and even touch each other, during the needle insertion step of a biopsy performance. Furthermore, contact of specific component pairs must never be considered as safety threats like the patient and the table. The collision avoidance system shall be aware of all components' current use-cases and allow close proximity of components as long as the interaction is desired at the time being. Therefore, the separation distance between bodies is adapted to the use-cases of the bodies.

The real-world therapeutic setup is not ideal; latency, braking distance, and quantification uncertainties have direct influence on the separation of the components. The proposed solution adds a buffer to the separation of components to ensure safety. Although the values of these constraints vary in time, they are assumed to be constant in order to reduce the complexity of the problem. In order to ensure safety, worst-case values of these constraints can be assumed for each component and body.

For detecting conflicts at a minimized separation between two bodies can be achieved by minimizing the individual separation distances around them. From a computational point of view, the abovementioned statements can be summarized in Equation 2-4. The required separation distance around a body b_j^m from its surrounding is:

$$\boldsymbol{d^{j}_{separation}(t)} = \boldsymbol{d^{j}_{inst}(t)} + \boldsymbol{d^{j}_{use}(t)} + \boldsymbol{d^{j}_{latency}} + \boldsymbol{d^{j}_{braking}} + \boldsymbol{d^{j}_{error}} + \boldsymbol{d^{j}_{minCom}}$$

Equation 2-4

where,

$d^{j}_{inst}(t)$	Separation due to the instantaneous velocity of the body; the displacement of the body between two successive updates. As the instantaneous velocity of a body varies in time, its contribution to the overall separation is also time varying.
$d^{j}_{use}(t)$	Separation due to the use-cases of the conflicting components. It can take

	different values in run-time; therefore, it is a time-varying function
$d^j_{latency}$	Separation due to latency in data transmission as well as the duration for signal processing duration. It is preset and constant in the run-time.
$d^j_{braking}$	The worst-case braking distance of the body; traveled by the body after receiving a stop command from the collision avoidance system until the body entirely stops. It is preset and does not vary in the run-time.
d^j_{error}	Buffer on the separation due to measurement uncertainties during quantification of the position and orientation of the body. It is preset and does not vary in the run-time.
d^j_{minCom}	The minimum allowed comfort distance around the body, a user-defined constant value.

As required by human-comfort aspects, a minimum required separation of a body b^m_j cannot exceed its maximum allowed comfort distance:

$$d^j_{separation}(t) \leq d^j_{maxCom} = \frac{v^j_{max}}{1\ sec}$$

Equation 2-5

Figure 2-5 depicts the adaptive separation $d^j_{separation}(t)$ around the body b^m_j, which can vary between the minimum and maximum allowed comfort distances in the run-time.

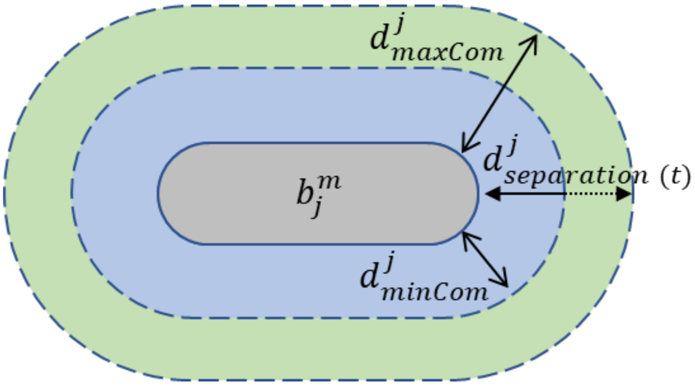


Figure 2-5: The adaptive separation around a body can vary in time and get values between the minimum and maximum comfort distances

The bodies b^m_j and b^n_k are in conflict if the actual distance between their closest points is less than the summation of $d^j_{separation}(t)$ and $d^k_{separation}(t)$. The minimum allowed distance between the bodies shall be so large that the collision avoidance system can detect the collision at this instance, take proper actions to resolve the conflict, and prevent the collision before it occurs.

2.2.4 Resolving Conflicts

Necessary actions to avoid collisions may vary among components. If the component-of-interest or its manipulator is an electronically manipulatable active component, the movement can be slowed down or completely stopped to avoid collision. On the contrary, if the component-of-interest or its manipulator is autonomous, it can be only warned rather than being slowed down or stopped. Maneuvering the component-of-interest around the obstacle is not in the scope of the proposed collision avoidance approach. It may be subject of future studies.

In case of conflict detection, the collision avoidance system shall trigger either full stop or slow-down action if the component-of-interest is electronically manipulatable. Trolley-based or ceiling-mounted components cannot be electronically stopped or slowed down because they are manipulated by a staff member. Therefore, the system shall warn the staff in such conflicts where the component-of-interest is a passive component manipulated by an autonomous component. Similarly, the staff shall be warned in case the patient table is being manually moved. The patient can either be moving together with the patient table or by him/herself. The patient table shall be stopped or slowed down if the patient is conflicting with an obstacle. Additionally, the staff shall be warned by the system about the conflict.

In the context of this study, the staff members are not considered as a component-of-interest but only as an obstacle. The system focuses on preventing interactions in which a staff member can be collided and excludes resolving conflicts in which a staff member gets into close proximity of any other component. In other words, the system takes no action against the staff.

Table 2-3 lists the appropriate actions, which the proposed collision avoidance system shall take with respect to the component-of-interest in order to resolve the conflicts.

		Applicable action in case of conflict detection		
		Full stop	Slow-down	Warning
Component-of-interest	Patient			✓
	Angiography system	✓	✓	
	Assistant robot	✓		
	Patient table	✓	✓	✓
	Trolley-based component			✓
	Ceiling-mounted component			✓

Table 2-3: Proper actions to be taken to avoid collisions with respect to the components of interest

2.3 Functional Requirements

Functional requirements of the system describe what the system does, its specific tasks, as well as its behavior under various circumstances. The dynamics of the environment, interactions between components, and needs for safety, agility, and comfort in the therapy suite, as investigated in Section 2.1 and Section 2.2, indicate the functional requirements of the collision avoidance system.

The proposed system shall be aware of the procedural context by referring to the use-cases of the components at the time being. Based on this awareness, the system shall distinguish between collaborative and destructive interactions of components. It shall detect the undesired proximities and prevent collisions as referring to the Table 2-2 in Section 2.1.3. It:

- Shall prevent catastrophic or critical collisions.
- Can prevent collisions with negligible impact.
- Shall not interfere with collaborative interactions or interactions which are out of scope.

In order to ensure safety and agility, the system shall assign adaptive separation distances between components as described in Section 2.2.3:

- It cannot assign a universal separation between all components; therefore, it shall allow unique and custom separation distances between specific body pairs.
- As constant separation distances between components cannot be assigned, the separation distances shall be time-varying and be adapted to instantaneous velocities of the bodies, update rate and use-cases of the components at any time instance (Equation 2-4).
- For the sake of safety, the separation zone around a body shall be as large as possible, while it shall be as small as possible for the sake of agility, as described in Section 2.2.1.

While observing the tradeoff between safety and agility, the proposed system shall achieve collision avoidance by fitting the required separation into human comfort range as described in Section 2.2.2:

- It shall prevent undesired vicinity of certain bodies at any time, independent of their velocity, if the distance between the bodies is lower than a user-defined minimum threshold (Equation 2-1).

- It cannot detect any proximity between certain bodies as a conflict if the distance between the bodies is higher than a user-defined maximum threshold (Equation 2-2 and Equation 2-3).

According to the characteristics of the conflicting components, the system shall take the proper actions to resolve the detected conflicts, as given in Table 2-3, and eventually prevent collisions.

2.4 Quality Requirements

On the contrary to functional requirements, the quality requirements of the collision avoidance system describe how the system achieves certain tasks and behavior.

Real-time performance: The proposed collision avoidance system shall primarily function in run-time throughout all procedural steps. It must perceive the environment, process received information in order to interpret them, detect conflicts, make proper decisions, and get the proper action to avoid potential collisions. Real-time performance guarantees that all necessary steps of conflict detection and collision avoidance are achieved in run-time before any collision occurs.

The amount of the data required for perception, interpretation, and decision-making must be minimized so that computation can be achieved in real-time. Long computational duration buries the risk of detecting the conflicts and getting the actions too late, that means, after the components collide with each other.

Extensibility: As described in Chapter 1, the composition of therapy suites will constantly change along the clinical and technological advancements. New therapies will be administered in the suite, accompanied by introduction of new components into the environment. Therefore, the collision avoidance system shall be extensible; must be open to introduction of new equipment, so it can answer the safety, agility, and comfort demands of the evolving therapy suites in the future. It must be flexible in terms of introducing new use-cases for the existing components. It must enable new desired and undesired interactions between components based on emerging clinical workflows.

User-centered operation: Staff members are the master within the therapy suite, assuming specialized roles and responsibilities. These human beings perform the diagnosis, plan the treatment, and decide which components are going to be used during the case and in which location they are going to be distributed. They carry out the procedure, operate on patient, and make ultimate decisions. Their work is not finished when the treatment is completed; they transfer the patient, replace the components to their storing locations.

Although the collision avoidance system shall detect conflicts between the primary components and can slow-down or entirely stop a component, it must not be the ultimate control mechanism over those components. It is the staff, which must have this overall control right, and the system must be compatible with the requirement that the user makes the final decision.

2.5 Associated Risks

Events and situations in the therapy suite setup are classified as risks if they have the potential to cause collisions despite the collision avoidance system. Risk factors are mainly related to quantification of positions and posture of the components as well as data transfer between components and the collision avoidance system.

Latency and quantification errors: While the analog to digital convertors shall provide the position and orientation data of component bodies throughout the entire time course of procedure, quantification inaccuracies shall remain in an expected range. That means components shall not be too late to report their movements to the system, i.e., the latency in runtime shall be below a presumed limit. If the latency of a component or the errors on its position and posture exceed the presumed worst-case numerical values in runtime, inconsistency between the reality and the computation may occur. In such a case, an appropriate separation zone around the body cannot be computed, conflicts cannot be detected in time, and collisions may not be prevented.

Loss of sight: Components, which cannot quantify their position and posture, are tracked by means of external quantification modalities. In case that there is an obstacle between the quantifying modality and the tracked component, the position and orientation of the tracked body cannot be quantified until the obstacle is removed. In consequence, the component can be subjected to a collision in the meantime.

Disconnection: Similar to the loss of sight problem of the optical tracking system, the C-arm, patient table, or the assistant robot may potentially lose their data connection to the collision avoidance system. In this case, they continue to move, but due to the disconnection the system lacks their position and posture information. This situation of unawareness may trigger collisions during the disconnection period.

Excessive speed: The collision avoidance system presumes constant maximum speed of each individual component in scope. If a component exceeds the presumed maximum speed in runtime, the associated separation around the body is smaller than the actual required one. The collision avoidance system may not detect the conflict in this case; therefore, a collision is likely to occur.

In summary, related to all these associated risks, performance of the collision avoidance system is not guaranteed under any of these circumstances. The development of overriding solutions in case of these risks has not been in the scope of this study. Instead, the system warns the user if data in run-time cannot be received from a component or a component exceeds its presumed maximum speed.

2.6 Performance Evaluation Criteria

The performance of the collision avoidance system can be evaluated by comparing the size of the separation distance at the time of conflict detection to the final distance between the bodies at the end of conflict resolution.

As the minimization of the computed separation between the conflicting bodies b_j^m and b_k^n at the instant of conflict detection is requested, the conflict detection performance is given by:

$$\textbf{Spatial Agility Score} = \frac{(d_{max} - d_{det})}{(d_{max} - d_{min})} \times 100 \qquad \textbf{Equation 2-6}$$

where d_{min} and d_{max} are given in Equation 2-1 and Equation 2-2, respectively.

Having the inequality $d_{det} \leq d_{max}$ stated as a requirement in Equation 2-2, negative Spatial Agility Score implies that the collision avoidance system violates the agility of the environment. The more the system can afford the proximity of d_{det} to d_{min}, the more the system improves spatial agility in the therapy suite.

The system shall perform within the range of human comfort perception: The system shall neither intervene with interactions of components when the distance between them is larger than d_{max}, nor allow a proximity of components less than d_{min}. Otherwise, human comfort is violated. Therefore, the Human Comfort Score becomes a step function:

$$\textbf{Human Comfort Score}= \begin{cases} 1, if\ d_{det} \leq d_{max}\ and\ d_{final} \geq d_{min} \\ 0, if\ d_{det} \geq d_{max}\ or\ d_{final} \leq d_{min} \end{cases} \qquad \textbf{Equation 2-7}$$

The proximity of d_{final} to d_{min} indicates the success of modeling the therapy suite, the difference between d_{det} and d_{final} is used to assess how reasonable assumptions in the representation of the therapy suite are. These together yield the conflict resolution performance of the system:

$$\textbf{Mismatch Assignment Score} = 100 - \frac{(d_{final} - d_{min})}{(d_{det} - d_{min})} \times 100 \qquad \textbf{Equation 2-8}$$

The proposed system shall improve not only spatial agility by allowing components to function in close vicinity but also temporal agility in the therapy suite; it allows fast motions of components and supports a quick execution of tasks. The Temporal Agility Score of the system for a given interaction can be computed relative to the safest version of that interaction. The travel duration of the interaction, t_{travel}, is compared to the travel duration of the slowest interaction, $t_{slowest}$:

$$\textbf{Temporal Agility Score} = \frac{(t_{slowest} - t_{travel})}{(t_{slowest})} \times 100 \qquad \textbf{Equation 2-9}$$

As a component-of-interest can achieve higher velocities, it carries out a particular interaction at a shorter duration, resulting in the increased temporal agility.

3

State of the Art

Collision avoidance concepts have already been developed for transportation applications like ocean navigation, civil aviation, and unmanned aerial vehicles. They have established the basic principles as well as the mathematical ground for solving collision problems. Development of collision avoidance methods for robotic applications has started with preventing collisions between a single robot and its surrounding. These concepts have later evolved to avoid collisions between multiple robots, as well as to enhance human-robot coexisting environments and human-robot interactions. These concepts have been implemented for industrial applications, and progressively grow towards other fields.

In the basic works on collision avoidance of robot-existing environments, assumptions made on technical constraints are far behind meeting the requirements of modern and future therapy suites. However, these works establish a strong basis for understanding the practical problem and characterizing the technical requirements in order to realize a suitable solution.

No collision avoidance system has been reported in the public domain, which aims at preventing the collisions between multiple, dynamic, independent, and heterogeneous components in 3D space, ensuring safety without compromising agility in therapy suites. This chapter analyses the basic collision avoidance studies in terms of their core considerations, scopes of technical constraints and relative assumptions, and their proposed solutions. It summarizes the implementation of reported collision avoidance systems at multiple-robot and human-robot interaction environments.

There are a limited number of studies, which focus on avoiding collisions in the clinical environments. Despite their shifted motivations and purposes, they contribute to this work by extending the practical perspectives and introducing future improvement opportunities. A brief overview of collision avoidance approaches for clinical environments and applications, reported in the literature and patents, is given. The advantages and disadvantages of these approaches in meeting the requirements of the comprehensive collision avoidance system for therapy suite are analyzed.

3.1 Basic Robotic Collision Avoidance Concepts

Early studies have focused on planning of a collision-free path and navigating in the environment for avoiding collisions in robotic environments. Provision of self-protection to the robot by maneuvering capabilities is essential among the proposed approaches. In the general setup, a robot is equipped to sense its proximity to the surrounding, identifies the distance between itself and the obstacles. When the minimum distance to an obstacle is less than a threshold, the maneuvering action is taken so that a potential collision is avoided. These studies mostly perceive the environment through a single robot, they assume that the robot has assigned a clear target and the movements take place in a two-dimensional (2D) plane. Kinematic representations of the objects are mostly ignored.

The Artificial Potential Field concept, introduced by Khatib, assigns a direction to the robot of interest based on attractive and repulsive forces [12]. The assigned target position must be known, which then applies an imaginary force to attract the robot towards itself. Unless any obstacle exists in the close proximity, the robot directly proceeds to the target. When the robot senses an obstacle with a distance less than a user-defined threshold, maneuvering action is activated so that the obstacle virtually repels the robot. The selection of the threshold depends on the maximum operating speed and the deceleration.

Moravec proposes the concept of Certainty Grids in which a robot obtains a geometric map of its neighborhood through a variety of sensing modalities [13]. The information from different sensors is fused to compute the probability of any existing obstacle at a particular grid on the geometric map. The robot accumulates the sensing information in time, hence has the ability to learn the environment. The robot navigates in the environment by simply selecting paths, which are identified to be clear, that means without any obstacles, on the certainty grid.

Borenstein and Koren bring the concepts of artificial potential fields and certainty grids together, leading to the Virtual Force Field approach [14]. A square window around the robot is assumed, and each cell of the certainty grid involved in this window either attracts or repels the robot. The magnitude of the applied force by each cell is a function of its certainty and the distance to the robot; however, no additional information on selection of the window dimension is given.

The Virtual Force Field approach is later improved by introduction of the Vector Field Histogram method [15]. Sticking to the basic principles of artificial potential fields and certainty grids, this method introduces the processing of acquired data for generation of a one-dimensional polar histogram, which facilitates the spatial perception of the obstacles. Direction and speed of the robot movement are then assigned accordingly. Adaptive thresholding of the polar obstacle density is proposed for fine-tuning the identification of clusters of obstacles. This adjustment buries the opportunity to navigate at higher speed and through narrow passages. The maximum allowed velocity and the data sampling rate has been taken into account for evaluating the performance of the approach.

Simmons proposes the Curvature-Velocity Method for a robot, equipped with sonar and laser sensors, in order to avoid obstacles by maneuvering along computed collision-free curvature paths [16]. The tradeoff between velocity, safety, and target-directedness is graded by an objective function, which depends on speed, distance traveled without collisions, and heading towards the target. Rotational and translational velocities, as well as the maneuvering direction, which maximizes the objective function, are assigned to the robot. The robot traveled in people environments with a maximum speed of 600 mm/sec, while the limiting factor to the speed has been reported to be the sampling rate of the sensors.

The Dynamic Window Approach assumes components moving along curvature paths, and considers pairs of rotational and translational velocities of a component at an instant [17]. A pair of rotational and translational velocities is distinguished as admissible if the robot has the ability to stop before contacting the closest obstacle on the path. The dynamic window limits the computation of velocities to those, which can be reached within a given time interval. The performance of the system is optimized by maximizing an objective function, which depends on speed, the distance to the closest obstacle on the trajectory, and heading towards the target.

Minguez and Montano propose Nearness Diagram navigation, assuming a holonomic robot with sensory equipment, which navigates over a flat surface through dynamic obstacles towards a given target [18]. Sensory information is utilized in order to determine the proximity of obstacles and to map clear areas geometrically in real-time; the direction of movement is assigned accordingly. A security zone around the robot is defined based on the maximum sensible range and a security distance bounding the robot.

Reciprocal n-body collision avoidance is proposed in order to avoid collisions between multiple robots moving in the same space [19]. Holonomic and independent robots with simple shapes are assumed to move on a 2D plane; the dynamics and kinematics are ignored. It is further assumed that each robot can perfectly sense the shape, position, and velocities of obstacles and other robots. A velocity-based avoidance method is implemented so that each robot assigns itself a velocity, which can be realized, and stays out of occupied zones.

The abovementioned studies propose local collision avoidance methods to maneuver a robot around an obstacle, in which each robot is responsible for perceiving its own surrounding. An avoidance strategy is activated when the distance between the robot and an obstacle falls below a critical value. The studies do not propose methods for calculation and optimization of a critical distance; they instead set the distance to a constant value.

Establishing a global collision avoidance approach requires, on the contrary to the local avoidance approaches, methods to determine the distances between the bodies of all components of interest. Gilbert, Johnson, and Keerth propose an algorithm, later named as GJK algorithm, which computes the Euclidean distance between two convex sets in R^m [20]. Having proper 3D shape representations of the components, this algorithm can either be utilized to compute the closest distance between two bodies or to detect contact in the global 3D space. Alternatively, Gottschalk, Lin, and

Manocha propose the OBBTree algorithm to determine contact and closest distances between polygonal models [21]. Rectangular bounding boxes, having an arbitrary orientation in the 3D space, are used to compute the proximity between complex models of the components. Täubig *et al.* introduce a solution to avoid self collisions of a humanoid robot [22]. The solution is based on the GJK algorithm; it monitors the separation between all pairs in run-time and determines the collision risks. This solution can be extended to other components and applied to therapy suites.

3.2 Improved Implementations and Applications

The literature search reveals that the prior studies ignore describing the systematic design of the critical distances and forbidden zones around the bodies, based on the shape and dynamics of a component [23]. Simplified assumptions, ignoring the shape, dynamics, and kinematics, introduce severe safety hazards due to unrealistic motion and occupancy representations [24]. The underlying algorithms, as described above, are implemented in later studies, and their performances are improved by making more realistic assumptions, together with broadened perspectives on applications.

3.2.1 Communication in Multi-Agent Environments

Dimarogonas *et al.* implement a method to avoid collisions between multiple independent robotic agents, which can autonomously navigate in the same workplace [25]. They propose that the decentralized collision avoidance approaches have an advantage over centralized approaches in terms of computational complexity and robustness. Through a central and global awareness, each agent can have the information on forbidden zones; they can progress towards their target without knowing the targets of the other agents. Mastellone *et al.* observe the environment through a color camera and process the images at a central computer, which knows the position and orientation of all robots in the image [26]. The robots further inform this central computer by broadcasting the requested position and orientation. Similarly, agents in a multi-robot navigation environment transmit their own information to a central "blackboard", they receive the information about the others from it, and process the received information individually [27].

On the contrary, Hennes *et al.* implement a decentralized collision avoidance system for multi-robot environments, in which all robots are equipped to mutually communicate with each other [28]. They point out that the entire system is blocked when the central unit fails, they establish an algorithm so that each robot informs others about its own velocity and position in the global coordinate system.

3.2.2 Human-Robot Coexisting Environments

Detection of people is vital for avoiding collisions between mobile robots and people in the same workplace. For the working efficiency, an avoidance strategy which represents humans properly is vital.

Tamura *et al.* equip a mobile robot with laser range sensors, which detect the legs of people, and applies Kalman filtering to track them [29]. Based on pedestrian motion models, they estimate the intention of tracked person, i.e., if he/she is trying to avoid the collision or not, and avoid the collisions accordingly. Marvel and Norcross provide an overview of speed and separation monitoring in collaborative robot work-cells [30]. Robot velocity, braking factors, update rate, and reaction durations are reported to have a significant effect on safety in human-robot coexisting environments. Measurement uncertainties and safety margins are to be considered for safe speed and separation monitoring methods.

Knepper and Rus propose an avoidance approach, based on the sociological findings on pedestrian navigation preferences in crowded neighborhoods [31]. The robot runs a prediction algorithm when it detects an obstacle in its own critical zone so that the human’s future trajectory is predicted and the avoidance algorithm takes the proper actions. On the other hand, Zeng and Bone point at unpredictable nature of the human-robot environments, making precise predictions is unlikely [23]. They state that an estimation of the future moving direction of a person is not satisfactory.

Baltzakis *et al.* fuse data from laser scanners and an optical camera, and obtain the metric depth mapping of the 3D space; the collision avoidance algorithm is run on this information after corrections [32]. Flacco *et al.* utilize Kinect cameras to determine the distances between dynamic components, including robots and humans, on 3D depth space data [33]. The distance computations are used to assign collision-free velocities to the joints of the robots to avoid collisions. Kaldestad *et al.* improve the utilization of Kinect cameras by parallel processing the depth space data on a GPU [34]. The resulting information is then utilized by the collision avoidance system for trajectory planning and torque control. Setting the update rate of the robot to 1 kHz, the spatial resolutions of the perceived spaces have been 10 mm and 5 mm, and the resulting processing durations have been 4.74 ms and 8.68 ms, respectively.

Human comfort in human-robot coexisting therapy suites must be ensured so that the staff can carry their tasks without stress and interruption. The distance of a robot to a human being has a significant impact on the human comfort in the therapy suite, where the human-beings and the robots function in the same space without any physical separation. Syrdal et al. investigate factors that influence human behavior in the presence of a companion robot [35]. Internal factors such as height, health status, gender, heart rate as well as external factors such as cultural norms and the situational context can have an effect on the threat perception and, hence, the comfort zone of a person. Billings et al. study the development of trust towards robot in human-robot coexisting environments and focus on the robot characteristics, which impact human comfort [36]. Robots’ size, appearance, and behavior at certain proximity impact the trust and human comfort.

Lasota and Shah analyze the effects of human-aware motion planning on close-proximity human-robot collaboration [37]. They express that the comfort zone depends on the end-effector speed of the robot; they propose to adjust the speed of the end-effector with respect to its distance to the surrounding objects.

3.2.3 Collision Avoidance in Clinical Environments

Ladikos, Benhimane, and Navab point at the increasing introduction of C-arms and robots into therapy suites, in which surgical tools, navigation systems, and monitors already exist, and underline the necessity for a collision avoidance system to speed up safe movements of the components [38]. They use 16 optical cameras to observe the 3D environment, followed by segmentation of acquired images by GPU processing in order to recognize objects in real-time. Separation zones around recognized components are formed, and intersecting separation zones are detected to identify a collision risk. When the system detects a person, entering into the working space of the C-arm, the system gives an alarm to the person who operates the C-arm. The frame rate of the cameras has been 30 fps in their experimental setup. The minimum safety distance during experiments has been set to 200 mm, however no detailed description has been provided on how the minimum safety distance has been chosen.

Morvan *et al.* propose a method to track the manipulators of a surgical robot, to detect possible collisions between the robotic arms in real-time, and to alert the operator [39]. They compute the closest points between the arms and detect the links, which are closer to each other than a given threshold. Their approach does not consider external components in the proximity of the robot, and the selection of thresholds is not described.

Nguyen *et al.* propose a collision avoidance method for the robot-assisted surgery, which takes patient movements into account and extends the perspective to collisions between the robot and the patient, but excluding collisions between robot links [40]. The optical tracking system is used to detect the positions and orientations of the robotic bodies and the patient body; an alternative motion path is calculated for the robotic end-effector in real-time in case a future collision is detected.

Beyl *et al.* equip the operating room with multiple time-of-flight cameras to track people and optical tracking system to track robots in the environment with the perspective on human-robot cooperation [41]. The closest distances between the neighboring bodies are computed, appropriate action is taken when the computed distance is detected to be a certain threshold. The operator of the robot is warned when the distance is lower than 400 mm, and the robot is automatically stopped when the distance is lower than 200 mm. Parameters affecting the threshold distance, hence the strategy on how to make the decision on the safety threshold, are not explicitly described.

3.3 Patents on Collision Avoidance in Clinical Environments

There is no patent, which reports on a comprehensive collision avoidance system for clinical applications, aiming at collisions between all components lying in the scope of this work.

Cho and Kim propose a system to allow multiple robots for cooperation on a complicated task [42]. The behaviors and states of individual robots are linked to each other to perform together; avoiding collisions with the external world is not addressed.

Olson focuses on remote catheter guidance systems and brings in the idea of avoiding collisions based on intra-procedural images between a medical device, manipulated in the patient, and the surrounding tissue or other neighboring robotically controlled medical devices [43]. Larkin reports a similar image-based approach to avoid collisions between the surrounding tissue and robot-manipulated surgical instrument [44].

Coste-Maniere *et al.* report a method for surgical planning, in which they implement a unit to detect internal collisions of a surgical robot, meaning that interferences between the arms are detected [45]. Hourtash *et al.* report a similar implementation [46]. They later report a system, which avoids collisions between manipulator arms and the patient [47].

Azizian *et al.* concentrate on heterogeneous devices and propose a system for coordinated motion [48]. They claim a shared interface between devices, through which the configuration, kinematic data, and planned path data can be exchanged. The system plans the first motion for a moveable element based on the present information and executes a motion command. Non-robotic devices are not in the scope of their work; hence the collisions cannot be avoided. Azizian, Kunze *et al.* propose a collision avoidance system, which avoids collisions between a surgical robot and a C-arm but leaves non-robotic devices out of scope [49]. Gregerson *et al.* report a similar system to avoid collisions of the end effector of a robotic surgical assistant with the patient or with the imaging device [50].

3.4 Comment on the State of the Art

Despite the fact that collision avoidance solutions exist in the commercially available components in the therapy suites today, the solutions are specific to certain components. Furthermore, a comprehensive collision avoidance system for the contemporary therapy suite is not available in the literature. A real-time collision avoidance approach is missing, which does not restrict the solution only to selected components, and which improves the safety of the environment and agility of the processes, enables the safe integration of the devices, and supports automation of the clinical tasks. Nevertheless, the collision avoidance algorithm by Täubig *et al.* is utilized as the primary method, and it is extended in this study for avoiding collisions in the therapy suite [22]. It introduces a method of object representation for reducing the computational cost. It implements the GJK approach for distance computations to detect conflicts in the 3D space. This algorithm is utilized as the basis for the collision avoidance system of contemporary therapy suites. It is extended within the scope of this study to represent the components in the therapeutic setup as well as to satisfy the specified requirements as outlined in Chapter 2.

As the literature search did not yield methods for evaluating the performance directly applicable to a comprehensive therapy suite collision avoidance system, performance indicators and corresponding evaluation methods and are introduced in the context of this study.

4

Solution Approach

There are multiple components in the therapy suite, while these components are stand-alone and unaware of each other: There is no interface between components to exchange data, which is required for collision avoidance computations. Components consist of multiple bodies and joints; furthermore, multiple components can move at any time instance. Under these circumstances, the computations of comprehensive and adaptive collision avoidance system cannot be achieved in the real therapy suite. Assigning proper separation zones around all bodies and mutually measuring the actual distance between the bodies cannot be achieved in real-time during a treatment.

In order to achieve the required computations in the course of a treatment and be aware of all components of interest, a digital twin of the therapy suite is formed. The digital twin is the representation of the real-world in the computational world: It contains all collision-related information of the components and represents their bodies and joints. It is aware of the desired and undesired proximities of bodies as well as the comfort distances around the bodies. The components are located in the digital twin in correspondence to their real locations.

The digital twin, as depicted in Figure 4-1, is the link between the computational algorithms and the real world. It is built prior to the run-time based on the physical and dynamic information of the components and it is kept up to date throughout the run-time. It collects run-time information from individual components, gathers all information from all components of interest in a central interface, and serves this cumulative information to the algorithms. By doing so, it generates global awareness of the entire therapy suite and enables real-time collision avoidance computations. The algorithms access to the up-to-date digital twin in run-time to assign adaptive separation zones around the components, identify conflicts, and decide on the proper actions to resolve the conflicts. The digital twin transfers the resulting actions back to the real components.

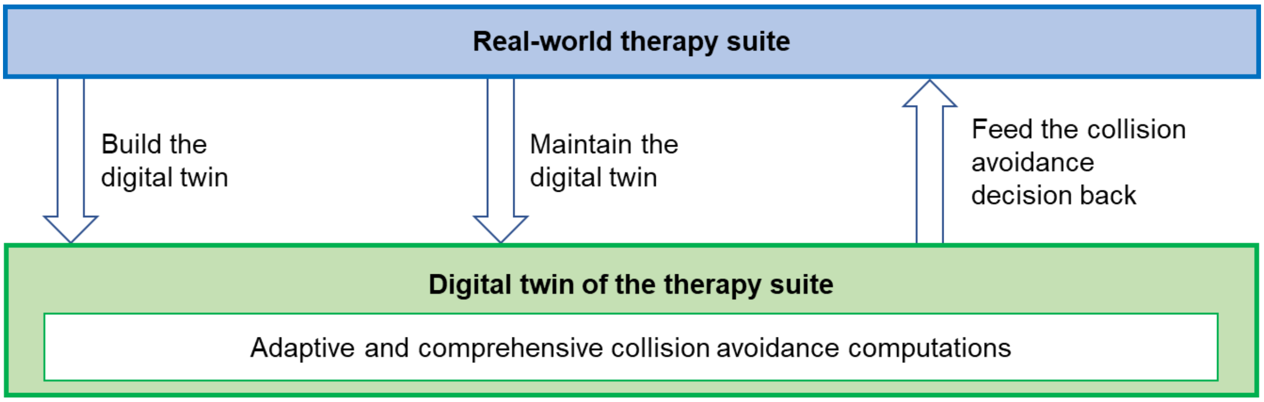


Figure 4-1: Digital twin of the real therapy suite is the interface between the real-world and the computational world, it enables collision avoidance computations in run-time.

This chapter first defines the theoretical background for introducing the real components to the digital twin; it introduces what parameters are necessary for describing physical and dynamic characteristics of components in the digital twin. It provides the mathematical relations for assigning adaptive separation zones around the components and identifying conflicts. In the second part, it explains how the digital twin is built and maintained as well as how adaptive and comprehensive collision avoidance computations are accomplished on the digital twin in run-time. Finally, it illustrates the solution architecture and process-flow of collision avoidance computations.

4.1 Theoretical Basis

This section describes definitions and assumptions for representing the stand-alone components and locating them relative to each other, which are prerequisite for forming the digital twin before the run-time. It explains the mathematical basis for assigning dynamic separation zones around the bodies, detecting the conflicts, and avoiding the collisions. This theoretical background is later utilized by the run-time algorithms in order to achieve collision avoidance on the digital twin.

4.1.1 Composition of the Therapy Suite

A therapy suite is a three-dimensional space, which is occupied by dynamic components. These components are distributed throughout the space, and the distribution varies in time as the components move or change their postures. The components are assumed to consist of one or more rigid bodies, where a body is the physical entity of a component which occupies a volume in the space and is subject to collisions. Each body is attached to a joint, which enables motion of a body and allows the component to change its posture. Therefore, the bodies determine the volume a component occupies, while the joints determine the dynamics of the component.

Setting up the therapy suite

The therapy suite S involves N components, where C^n is an individual component and N is a positive integer:	$S = \{[C^n]_{n=1}^{N}\}$	**Equation 4-1**
The component C^n consists of M rigid bodies, where M is a positive integer:	$B^n = \{[b_m^n]_{m=1}^{M}\}$	**Equation 4-2**
The component C^n consists of L joints, where J^n is the complete list of all joints of C^n and L is a positive integer:	$J^n = \{[j_l^n]_{l=1}^{L}\}$	**Equation 4-3**

The connections of joints of a component relative to each other are defined in an order, namely the kinematic hierarchy. The root joint is the parent of the rest of joints, it represents the local coordinate system of the component, and its position and orientation in a global coordinate system is known. Child joints are linked to the root in a tree-structure. The joint closer to the root joint is referred to as a proximal joint, and the one being farther from the root is referred to as a distal joint.

Each body is attached to a unique joint, while a joint may have multiple bodies attached to itself. Abstract joints are utilized to describe the relation between two bodies, although there is no physical link in between. Kinematic characteristics of components in the therapy suite are represented by revolute and prismatic joints, which simplify the numerical problem. In this way, a joint's coordinate system moves along a single axis of the preceding joint coordinate system. In case of a body moving in multiple axes with respect to the preceding body, abstract joints can be assumed between the two bodies so that each joint has only a single degree-of-freedom. The table-top, as an example, can laterally and longitudinally move with respect to the table-base. In order to model these two movements, two prismatic joints are assumed between the table-top and the table-base. Similarly, the base of a component, such as a trolley, can move on the ground; this mobile base has been assumed to have three joints: two prismatic joints to represent the lateral and the longitudinal movements, and a revolute joint to represent its rotations around itself. In the same manner, spherical joints can be represented by making use of multiple revolute joints. As a result, each joint moves along only a single axis of the preceding joint coordinate axis.

Joints of a component can have different characteristics in terms of maximum velocity and worst-case braking distance. The maximum achievable velocity of a joint is given as angular velocity if the joint is revolute, and linear velocity if the joint is prismatic. The worst-case braking distance is the maximum distance a joint travels after a brake until it entirely stops. It is given as an angle if the joint is revolute, and as a line segment if the joint is prismatic. Kinematic configuration of a component is the list of joint values in the hierarchical order.

4.1.2 Static Volume Representation of Components

Triangular surface mesh models contain precise and detailed shape representation of a body. However, detailed representation of bodies requires higher computational power. Precise surface representation of bodies is not required for collision avoidance purposes. The precision of the shapes can be reduced so that the volume of the body is represented approximately, and the collision avoidance computations can be achieved before the collision occurs.

In order to address the tradeoff between a precise shape representation and the computation duration, the bodies of the components are represented as sphere swept convex hulls (SSCH) of points. A finite set of points $\boldsymbol{P}$ in the body are determined as pivots, around which identical spheres of radius $\boldsymbol{r}$ are formed. Täubig, Bäuml, and Frese describe how swept volumes of an object are obtained from CAD models of that object and provide the mathematical derivation [22], [51]. Representing the volumes based on the SSCH provides computational efficiency as it avoids complex details of shape and represents the objects with few points. Figure 4-2 visualizes the volume representation of C-arm's detector as an exemplary body.

Static volume representations of the bodies

The body b_m^n of the component C^n can be represented by K numbers and identical radius of r_m^n around them:

- $p_m^n|_{BCS}$, list of 3D coordinates of the points in the body coordinate system, where

$$p_m^n|_{BCS} = \{[p_k]_{k=1}^{K}\}$$ **Equation 4-4**

- $\vartheta_m^n(r_m^n,\ p_m^n|_{BCS})$, volume representation of the body, generated by convolving the points $p_m^n|_{BCS}$, which are surrounded by identical spheres with radius of r:

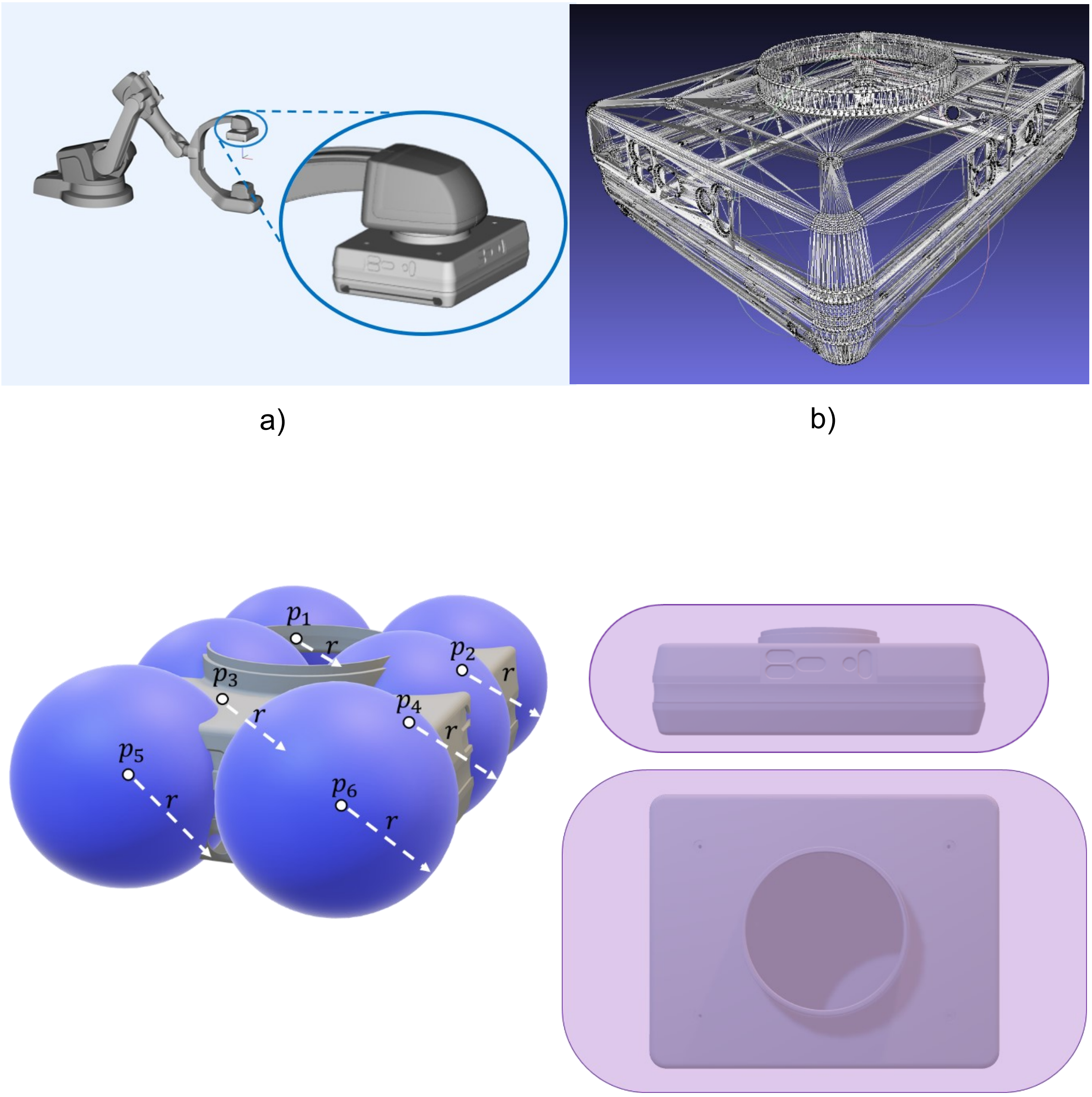
$$\vartheta_m^n(r_m^n, p_m^n|_{BCS}) = conv(p_m^n|_{BCS}) + \{f \in \mathbb{R}^3 \mid |f| \leq r_m^n\}$$ **Equation 4-5**

- Volume representations of all bodies of the component are then

$$\{[\vartheta_m^n(r_m^n, p_m^n|_{BCS})]_{m=1}^{M}\}$$

Remarks

- Volume representation $\vartheta_m^n(r_m^n, p_m^n|_{BCS})$ of the static body b_m^n is accomplished. Influences from movements are not yet included.
- Location of a body with respect to the other bodies of the same component is not yet obtained.



a) b)

c) d)

Figure 4-2: (a) Surface representation of the robotic C-arm by using triangular meshes (b) The surface representation of its detector consists of 6 data points (c) 6 identical spheres around the data points (d) Side- and top-view of the corresponding swept volume representation of the detector

The SSCH algorithm is further utilized to physically relate the bodies of a component to each other. Denavit-Hartenberg parameters are used to describe the forward kinematics of the components and relate the joints to their neighbors. Volume representations of the bodies are linked to their parent joints. Eventually, all points within the component are located relative to each other in the local coordinate system of the component.

Static volume representations of the components

Assuming the bodies $\{[\vartheta_m^n(r_m^n, p_m^n|_{BCS})]_{m=1}^M\}$ of a component C^n attached to their corresponding joints J^n, Denavit-Hartenberg parameters yield the 3D coordinates of the volume representations of the bodies in the component coordinate system is

$$\{[\vartheta_m^n(r_m^n, p_m^n|_{CCS})]_{m=1}^M\}$$

for a given kinematic configuration Ψ^n of the static component, where $p_m^n|_{CCS}$ is the list of 3D coordinates of the points in the component coordinate system.

Remarks

- Each point is linked to its parent joint, it follows the movement of the parent joint.
- Bodies are interlinked to each other; therefore, the distal bodies follow the movements of the proximal joints.
- The volume representation is given for a static component.
- For any given kinematic configuration, 3D coordinates of any point can be computed with respect to the local coordinate system of the component.
- The kinematic configuration of the component is not time-varying yet as the component is assumed stationary.
- The base location of the component in the environment is still unknown; therefore, the bodies cannot be located to the bodies of another component yet.

The SSCH approach is introduced for representing the humanoid and industrial robots; hence the utilization of it in the suite setup is not straightforward. Within the context of this study, the CAD-representations of the components are modified to match therapy suite-specific requirements to the SSCH approach. Direct application of SSCH representation to C-arm, for instance, does not allow any other component to penetrate the volume between the X-ray source and the detector. This situation is not acceptable as in the usual setup, the patient table and patient must penetrate this volume for imaging purposes. In order to remove this inconsistency, the C-arm is divided into sub-components, and the SSCH around each sub-component are computed separately. Eventually, the SSCH around the C-arm is reduced to an acceptable size so that other components can freely penetrate as it happens in reality.

4.1.3 Components on the Common Coordinate System

The volume representations of the components do not include any information on how those components are distributed in the environment. In order to achieve a global awareness, all components in the therapy suite are registered to a common coordinate system so that the distances between any two bodies can be relatively computed.

Base transformation of a component in global coordinate system

The 4x4 transformation matrix of the local coordinate center of component C^n is

$$BT^n = \begin{bmatrix} Rotation^n & Translation^n \\ 0 & Scale^n \end{bmatrix} \qquad \textbf{Equation 4-6}$$

where $Rotation^n$ is the 3x3 rotation matrix, $Translation^n$ is the 3x1 translation vector, and $Scale^n$ is the scale factor of the local coordinate center of the component C^n with respect to the global coordinate system.

Remark:

- Having the base transformation of a component with respect to the global coordinate system and its kinematic configuration, the static volumes of the component can be properly located in the therapy suite with respect to the global coordinate system.
- The volumes of component C^n in global coordinate system are represented as $\{[\vartheta_m^n(r_m^n, p_m^n|_{GCS})]_{m=1}^M\}$, where $p_m^n|_{GCS}$ is the list of 3D coordinates of the points in the global coordinate system.

Horn's quaternion-based method is utilized to solve the rigid-body transformation of two coordinate systems. It is the preferred method for coordinate system registration as it only requires the coordinates of multiple non-collinear markers in the two coordinate systems as input; returns the rotation, translation, and scale factor as output.

Let R denote the 3D coordinates of markers in a component's local coordinate system, and T denote the 3D coordinates of the markers in the global coordinate system:

$$R = \begin{bmatrix} r_{1x} & r_{2x} & r_{3x} & r_{4x} \\ r_{1y} & r_{2y} & r_{3y} & r_{4y} \\ r_{1z} & r_{2z} & r_{3z} & r_{4z} \end{bmatrix}$$

$$T = \begin{bmatrix} t_{1x} & t_{2x} & t_{3x} & t_{4x} \\ t_{1y} & t_{2y} & t_{3y} & t_{4y} \\ t_{1z} & t_{2z} & t_{3z} & t_{4z} \end{bmatrix}$$

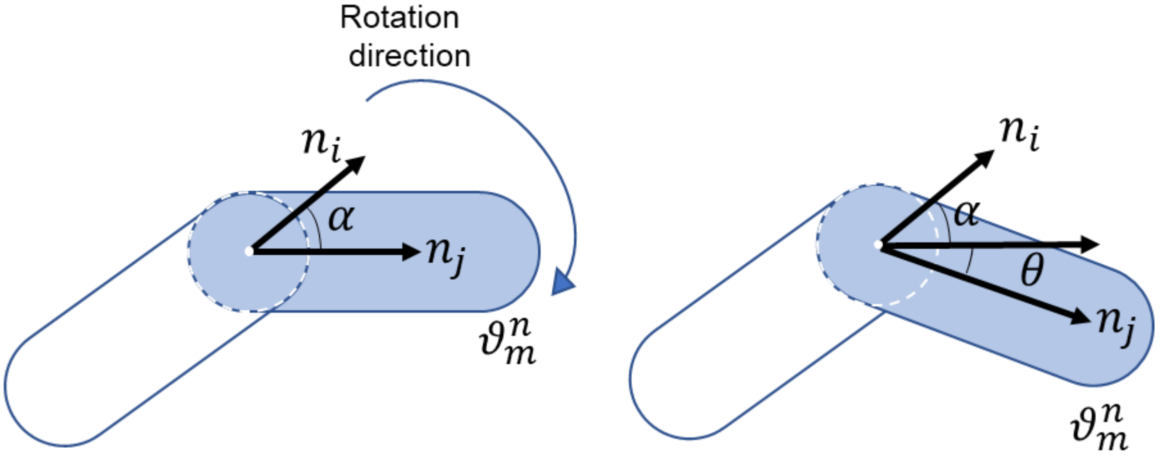
Giving R and T, Jacobson's Matlab script solves the transformation problem based on Horn's method and returns the base transformation matrix BT^n as given in Equation 4-6.

4.1.4 Dynamic Volume Representation of Components

The static volume representations of the components are not capable of adapting to the instantaneous velocities of joints as well as the use-cases and the update frequencies of the components. These static representations are extended to meet these requirements, resulting in the dynamic volume representations of the components.

4.1.4.1 Adaptive Joint Intervals

Given the value of a moving joint $\mu_l^n(t) = \alpha$ at a time instance, and if the joint immediately starts braking, it can entirely stop at the joint value $\eta_l^n(t) = (\alpha + \theta)$ [22]. $[\mu_l^n, \eta_l^n]$ is then referred to as the interval of the joint. Figure 4-3 and Figure 4-4 depict the joint values and joint intervals of bodies moving along a revolute joint and prismatic joint, respectively.



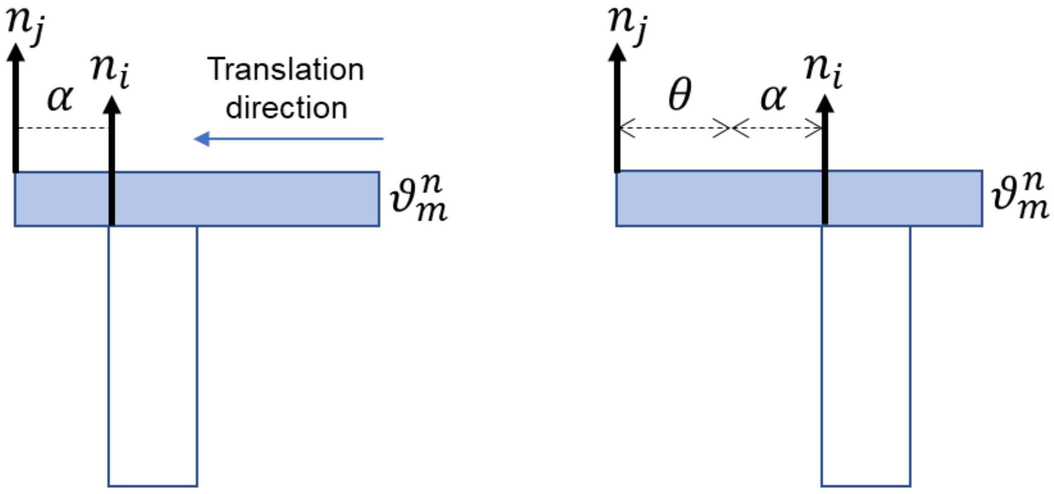
a)

The body b_m^n rotates around its parent revolute joint j_m^n. The joint value $\mu_l^n(t) = \alpha$.

b)

$[\alpha, \theta]$ is the computed joint interval: If the body immediately starts braking, it can stop at the joint value $\eta_l^n(t) = (\alpha + \theta)$.

Figure 4-3: (a) Joint value of a revolute joint. (b) The corresponding joint interval



a)

The body b_m^n rotates around its parent revolute joint. The joint value $\mu_l^n(t) = \alpha$.

b)

$[\alpha, \theta]$ is the computed joint interval: If the body b_m^n immediately starts braking, it can stop at the value $\eta_l^n(t) = (\alpha + \theta)$.

Figure 4-4: (a) Joint value of a prismatic joint. (b) The corresponding joint interval

The computed joint interval depends on the instantaneous velocity $\vec{v}_l^n(t)$ of the joint, uncertainty of the joint, and braking distance of the joint as well as the associated latency of the component. As the velocity increases, the interval of the joint eventually gets larger; the volume which can be touched by the connected bodies grows consequently.

Velocity-adaptive joint intervals

For a given kinematic configuration $\Psi^n(t)$ and instantaneous joint velocities $\vec{V}^n(t)$ of the component C^n

$$\Psi^n(t) = \{[\mu_l^n(t)]_{l=1}^L\} \qquad \textbf{Equation 4-7}$$

$$\vec{V}^n(t) = \{[\vec{v}_l^n(t)]_{l=1}^L\} \qquad \textbf{Equation 4-8}$$

list of intervals for all joints $\Phi_{velocity}^n(t)$ is obtained, where

$$\Phi_{velocity}^n(t) = \{[\eta_l^n(t)]_{l=1}^L\} \qquad \textbf{Equation 4-9}$$

Remark:
$\vec{V}^n(t)$ and $\Phi^n(t)$ are ordered following the kinematic configuration.

The computed joint intervals are extended by taking the contribution of the update rates of the components into account. Considering that the body continues its motion during two update signals, a safety buffer must be applied to the associated joints. Assuming constant velocity, this buffer must grow for lower update rates and it must shrink in response to higher update rates. Contribution of the update rates to the interval is given as the joint's displacement during two update signals. The additional interval of the joint l of the component C^n is given as δ_l^n:

$$\delta_l^n(t) = \frac{\vec{v}_l^n(t)}{\Delta u^n(t)}$$ **Equation 4-10**

where

$\vec{v}_l^n(t)$: Instantaneous velocity of the joint.

$\Delta u^n(t)$: Duration between the two succeeding update signals of the component.

Update rate-adaptive joint intervals

Given the list of velocity-adaptive intervals $\Phi^n(t)$ of component C^n and the duration between the two succeeding update signals of the component $\Delta u^n(t)$, velocity- and update rate-adaptive interval of the joint j_l^n is given as

$$\rho_l^n(t) = \eta_l^n(t) + \delta_l^n(t)$$ **Equation 4-11**

The intervals of all joint of the component are then given in the kinematic hierarchy as

$$\Phi^n(t) = \{[\rho_l^n(t)]_{l=1}^{L}\}$$ **Equation 4-12**

Remarks:

The resulting intervals of all joints of the component, $\Phi^n(t)$, are adapted to the instantaneous velocities of the joints as well as to the update rate of the component at the time being.

4.1.4.2 Volume Representations of Dynamic Components

The static volume representation ϑ_m^n of a body b_m^n is swept along the interval of its parent joint j_m^n to determine its dynamic volume representation. The dynamic volume representation of a body is the total volume the body can span throughout its movement until it entirely stops in case of immediate braking, as depicted in Figure

4-5. The cartesian displacement of a point due to the angular velocity of a revolute joint gets larger as the point gets farther from the joint. Eventually, the swept volume of the body along the interval grows as the body points are away from the joint.

Indeed, movement of a joint influences the swept volumes of preceding bodies. In this case, the joint interval of a proximal joint affects the swept volumes of all distal bodies. Furthermore, a component can have multiple joints instantaneously moving. The total swept volume of a dynamic component, $\mathcal{C}^n(t)$, is the total volume the component can span throughout its movement until it entirely stops in case of immediate braking. $\mathcal{C}^n(t)$ is obtained by successively including the sweeping effect of all joints to the preceding bodies, it is depicted in Figure 4-6.

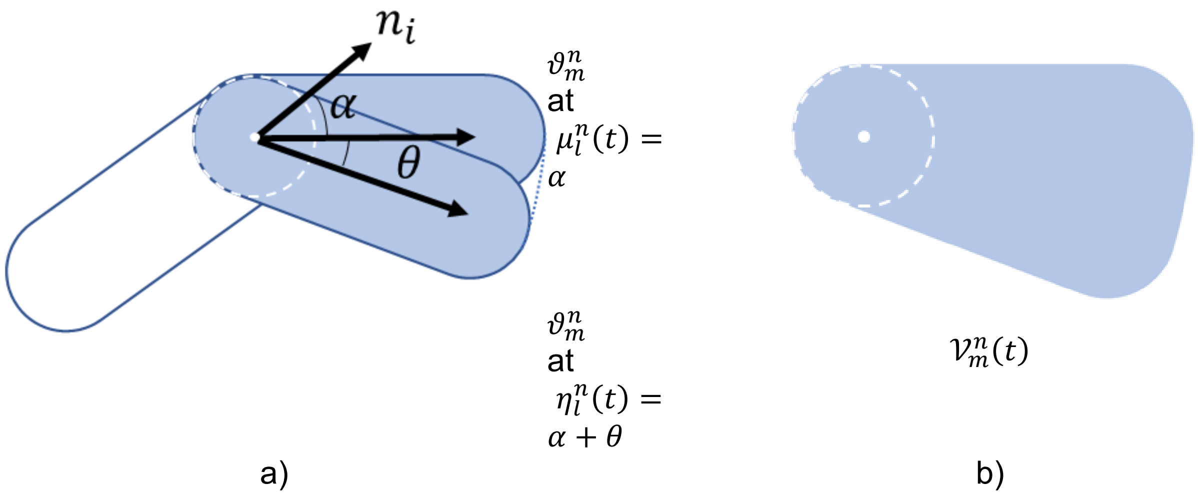


Figure 4-5: (a) The value of a joint associated with the body b^n_m is given to be α, corresponding joint interval at the time being is computed as $[\alpha, \theta]$. (b) The swept volume of the body at the time being corresponds to the interval.

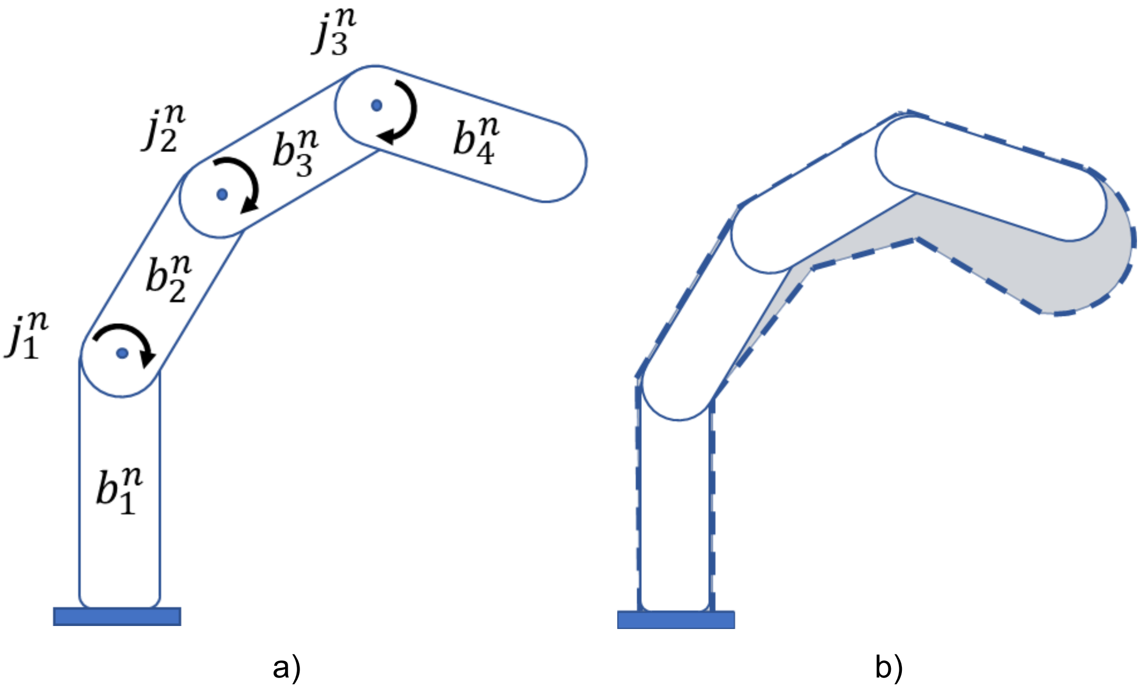


Figure 4-6: (a) The total swept volume of a component is obtained by aggregating the swept volumes of individual bodies along the kinematic hierarchy. (b) Intervals of the proximal joints contribute to the intervals of distal joints, resulting in larger swept volumes around distal bodies.

The swept volumes are time varying as they are related to the joint intervals. The associated volume grows together with the joint interval in the direction of motion. As a joint moves faster, the swept volume of a component gets larger.

4.1.4.3 Dynamic Separation Distance around a Body

The swept volume representation of a dynamic component ensures safety along its movements and prevents collisions. Nevertheless, it does not meet the human comfort requirements, it further neglects the influence of the use-case of a component on its separation. The volume representation of the bodies is extended to make the volume representations meet the specific requirements of the therapy suite.

Volume of a body $\vartheta_m^n|_i(r_m^n, p_m^n|_{GCS})$ in the $\mathcal{C}^n(t)$ is surrounded by a separation zone to ensure that the collision avoidance system satisfies the human comfort requirement and adapts to the use-case of the component. Denoting the separation distance around the body $\vartheta_m^n|_i$ as ${d_{separation}}_m^n(t)$:

$$d_{separation}{}_{m}^{n}(t) = \begin{cases} d_{minComfort}{}_{m}^{n}(t), & No\ active\ use-case \\ d_{useCase}{}_{m}^{n}(t), & Active\ use-case \end{cases}$$ **Equation 4-13**

where

$d_{minComfort}{}_{m}^{n}(t)$ is the user-defined minimum comfort distance around the component,

$d_{useCase}{}_{m}^{n}(t)$ is the user-defined separation, corresponding to a specific use-case of the component. The separation zone around a body based on $d_{separation}{}_{m}^{n}(t)$ is depicted in Figure 4-7.

Adaptive separation around a body and its dependencies were described as a requirement in Section 2.2.3. Equation 2-4 described the adaptive separation distance around a body as a function of instantaneous velocity, use-case, latency, braking distance, uncertainty, and minimum comfort distance, while the separation is described as a function of only use-case and minimum comfort distance in Equation 4-13. The contribution of the instantaneous velocity, latency, braking distance, and measurement uncertainty are considered during the computations of joint intervals. Therefore, the adaptive separation around the body as described in the requirements analysis is achieved.

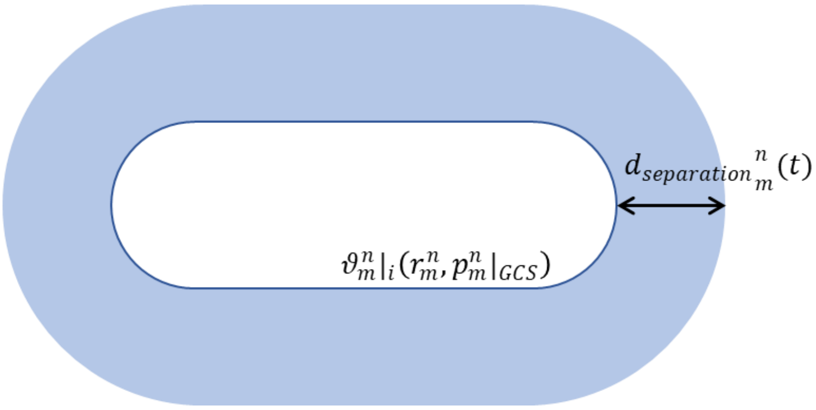


Figure 4-7: The separation zone around the volume representation of a body is the virtual volume, obtained by surrounding the body by the computed separation distance in all directions.

4.1.5 Detecting Conflicts

Given the swept volumes of all bodies corresponding to their movements and the separation distances around them at a time instance, the shortest distances between all body pairs are computed. The bodies b_m^n and b_v^y are in conflict if the distance $d(t)$

between the swept volumes of the two bodies is less than or equal to their total separation distances:

$$d(t) \leq d_{separation}{}_{m}^{n}(t) + d_{separation}{}_{v}^{y}(t)$$

where $d_{separation}{}_{m}^{n}(t)$ and $d_{separation}{}_{v}^{y}(t)$ are the separation distances around the bodies ϑ_m^n and ϑ_v^y at the time being, respectively. The vicinity of conflicting bodies and the relation of their separation zones are depicted in Figure 4-8.

If the proximity of the body pair is desired at the time, depending on the use-cases of the components C^n and C^y, it is excluded and not classified as a conflict.

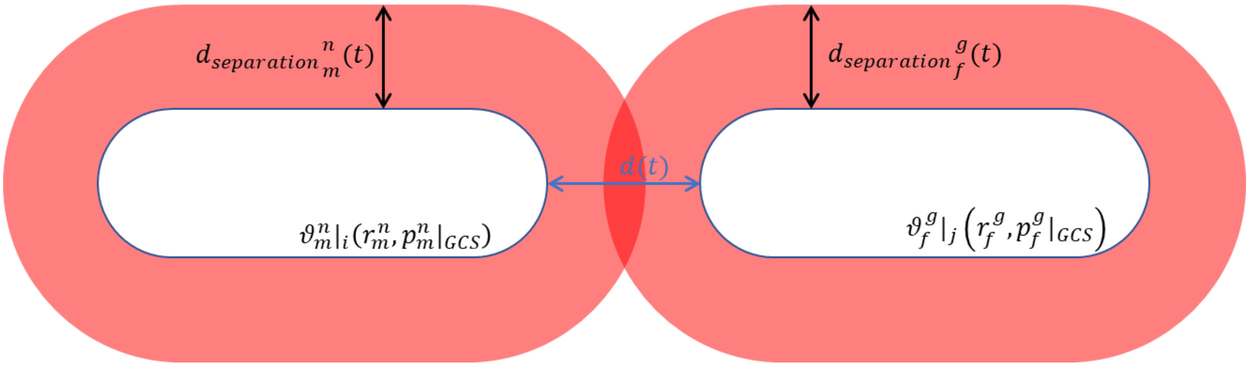


Figure 4-8: Two bodies are in conflict if their separation zones overlap and the proximity of the pair is undesired.

4.1.6 Avoiding Collisions

When a conflict is detected, proper measures are taken to resolve this conflict and to avoid a collision between these bodies. The actions depend on the types of the corresponding components as further described below:

Warning: If one of the conflicting components is a human-being or a human-driven component, an audio warning to the environment is provided.

Slow-Down: If a motorized component is involved in a conflict and that component is in a desired vicinity of another component, the velocity of the bodies of that component are reduced to the half of the current velocity. The component continues its motion towards the obstacle at a safer velocity under the observation of the operator until a certain minimum allowed vicinity is reached. In this manner, the agility of the system is increased while eliminating the undesired stop signals; the components can span larger spaces.

Stop: If a motorized component is involved in a conflict, in which the vicinity of the component to the obstacle is undesired, the component is entirely stopped by the collision avoidance system.

4.2 Solution Architecture

The digital twin is a 3D representation of the therapy suite together with the physical and dynamic characteristics of the components. It does not only provide information about where the components are, but also about their kinematics, use-cases, required comfort distances around bodies, and movements of the joints. Nevertheless, the digital twin itself has no interface to the real world nor it does collision avoidance computations.

The entire process of collision avoidance in the therapy suite is divided into tasks. A functional unit is a block of the collision avoidance system, responsible for carrying out a specific set of tasks, as shown in Figure 4-9:

- Since the digital twin is the prerequisite for collision avoidance computations, firstly the digital twin shall be built. Digital Replication Unit (DRU) builds the digital twin of the therapy suite before the run-time. The digital twin as a result of Digital Replication Unit is static, it has no interfaces to the real therapy suite.
- Central Registration Unit (CRU) is the run-time interface between the digital twin and the real world; it gathers information of all components of interest in the real therapy suite and brings into a central register. It feeds the results of collision avoidance computations back to the real world. Therefore, it achieves bi-directional communication between the digital twin and the real world.
- Perception Unit (PU) progressively maintains the digital twin in run-time based on the information coming through Central Registration Unit. It provides global awareness of the entire therapy suite so that the computational algorithms achieve their tasks on the up-to-date digital twin.
- Separation Assignment Unit (SAU), Conflict Detection Unit (CDU), and Conflict Resolution Unit (CResU) achieve adaptive collision avoidance computations on the up-to-date digital twin.

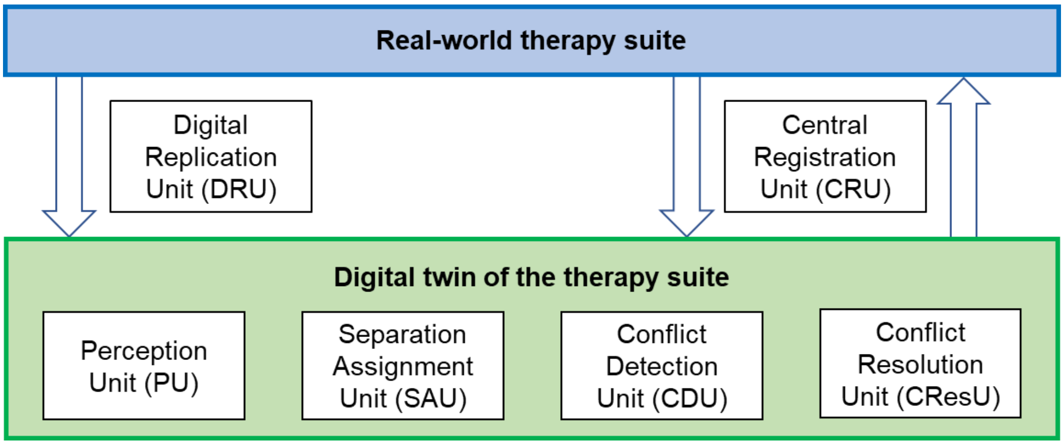


Figure 4-9: Functional units of the collision avoidance system, their relations to the digital twin and the real-world therapy suite.

A functional unit is referred to as offline if it does not have any tasks during the run-time, and online if it has tasks to prevent collisions in run-time. DRU is the only offline functional unit, as it accomplishes the assigned tasks before the run-time. The initial formation of a digital twin is not achieved in run-time; thus, it does not necessitate real-time connection to the components. Figure 4-10 shows the input-output relation of DRU while building the preliminary digital twin of the real therapy suite. This preliminary digital twin is static, there is no information flow from the components to the collision avoidance system.

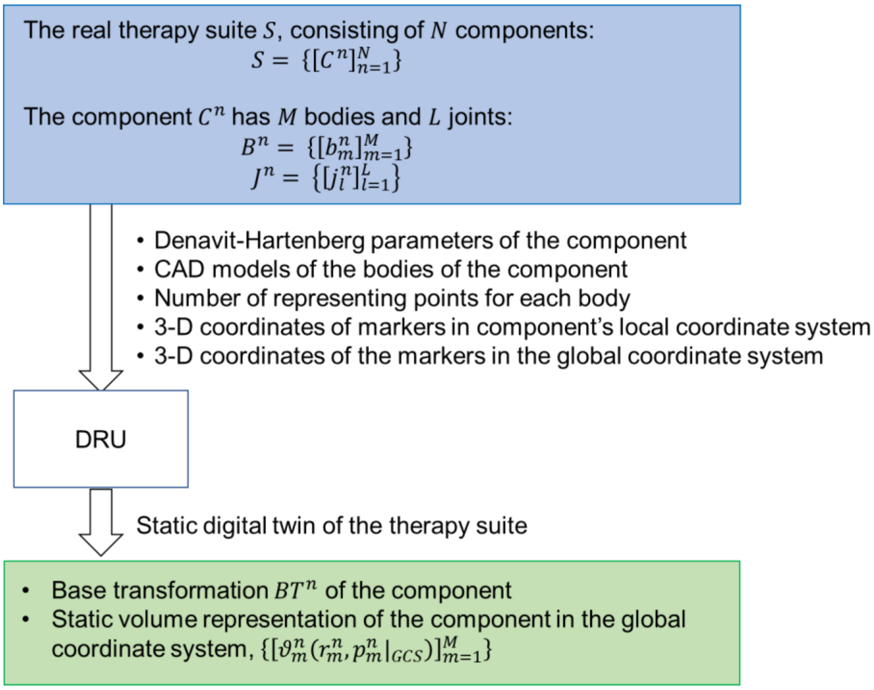


Figure 4-10: Building the preliminary digital twin of the real-world therapy suite before run-time by the offline functional unit DRU

The collision avoidance system is based on the central registration of the component-related data. The system architecture assumes a component-to-center communication method instead of a component-to-component communication method. The client-server approach of the TCP/IP is implemented in the solution so that each component is a client and connects to the central server. Each component transmits individual information to the central unit CRU; this unit gathers the information from all connected components and updates the component-database.

TCP/IP is preferred as the communication protocol since most of the components in the therapy suite are either equipped with the related hardware or can easily be interfaced by the help of a personal computer. It achieves a fast and reliable transfer of the data; therefore, it allows real-time performance. It is operating-system independent; it does not exclude any component or processing unit due to its operating system. This situation improves the extensibility and easy integration aspects of the collision avoidance system.

CRU interfaces the components not only for receiving data from them, but also for returning feedback from the collision avoidance system to them. The CRU is the only functional unit getting into direct interaction with the components.

Registered data flows mono-directionally between the functional units. CRU transfers the registered data to the PU for updating the digital twin of the environment. SAU works on the up-to-date digital twin and assigns separation adaptive distances around the bodies of the components with respect to the actual parameters. This information is then handed over to the CDU, which checks if any conflicts exist between bodies. In case of a conflict detection, the CResU determines the appropriate action to avoid the collision and reports this decision to the CRU. Finally, the CRU delivers the decision back to the conflicting components. The flow of information between components and the collision avoidance system as well as the input-output relations of online functional units are shown in Figure 4-11.

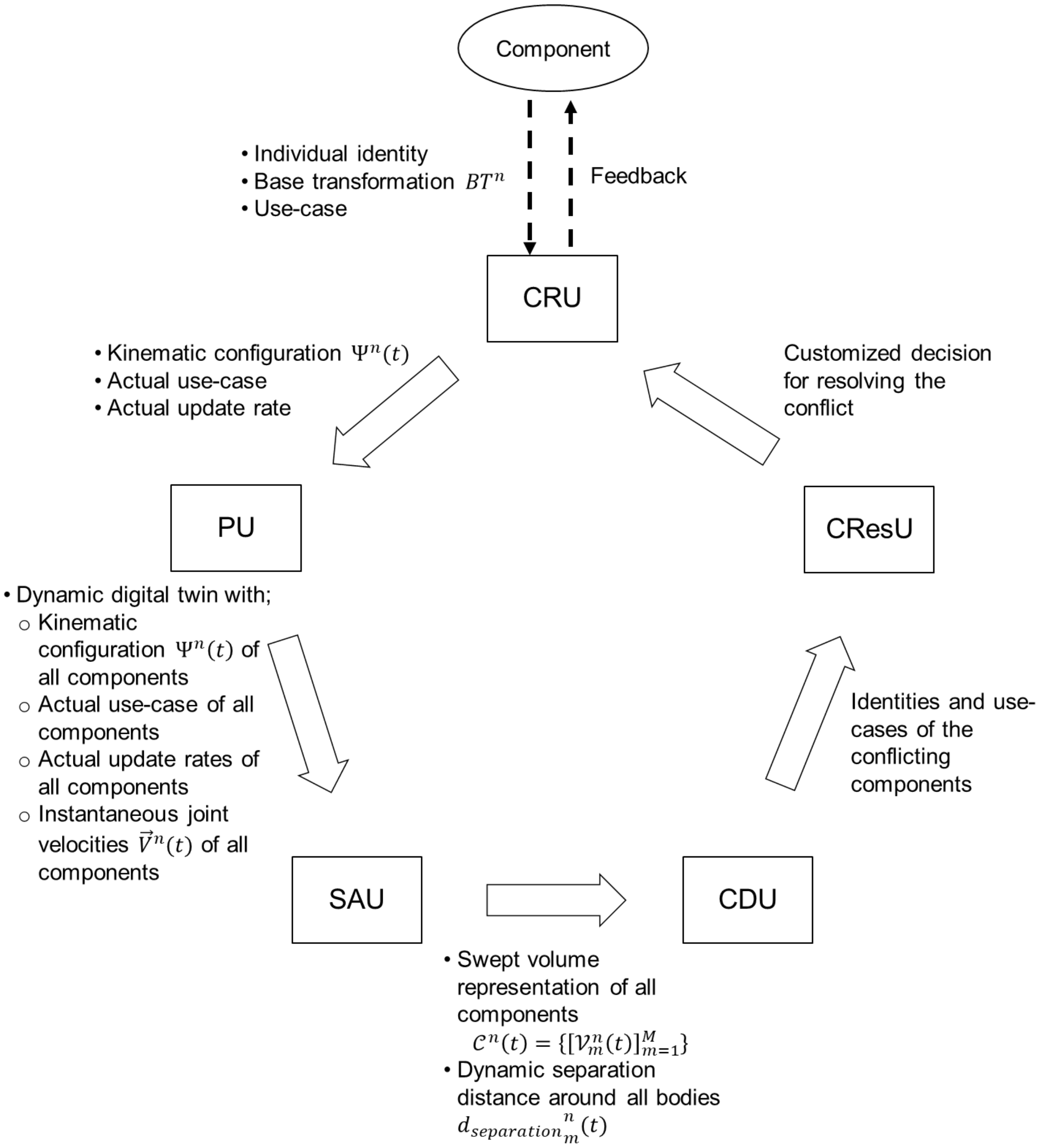


Figure 4-11: Run-time flow of information and relations between the online functional units

4.3 Functional Units and Their Tasks

In this section, the functional units and their corresponding tasks are described, by which processes they achieve these tasks are analyzed in detail.

4.3.1 Digital Replication Unit

The Digital Replication Unit creates a digital twin of the therapy suite before the execution of the collision avoidance computations and sets the basis for the other functional units.

Characteristic data of a component, which is prerequisite for collision avoidance computations, can be classified as static and dynamic data. Static data of a component have a fixed value, and its value does not change in run-time. On the contrary, the dynamic data of a component changes in run-time, hence, cannot be set to a fixed value. The DRU basically forms a component-database, stores the static data of the components and reserves places for dynamic data. While serving the stored data to online functional units in run-time, it allows them to update the dynamic data in the component-database.

4.3.1.1 Formation of the Component-Database

The component-database is a text file which contains the characteristic data of components. The characteristic data is classified into common attributes, body-specific attributes and joint-specific attributes.

The common attributes describe the identical properties of the component and are valid for all of its bodies and joints. Table 4-1 lists the common attributes of components and introduces their content, how they are acquired, and why they are relevant for the collision avoidance.

	Content	Acquisition	Relevance
Identity	Name of the component as the unique identifier	User-defined	Utilized to identify each component
Denavit-Hartenberg parameters	Denavit-Hartenberg parameters to attach reference frames in hierarchical order to the joints and represent the joints relative to each other.	Acquired from producers of commercially available components; user-generated for humans and customized solutions	Utilized to represent the posture of the components and to determine the volume occupied by the bodies
Base transformation	The position and orientation information of the component base with respect to the global coordinate system	Experimentally obtained as described in Section 4.3.1.2.	Prerequisite to bring all components in a common coordinate system
Latency	The time difference between the actual start of a motion and its perception by the collision avoidance system	Based on the datasheet of commercially available components and measurements	Utilized to assign safety buffers around the bodies of the component
Use-cases	Specific tasks the component carries out throughout procedures, and corresponding minimum separation distances around the bodies	User-defined	Utilized to assign the proper separation around the bodies of the component
Type	The category, which the component belongs to	User-defined based on the categorization in Chapter 2	Utilized for making the right decision to resolve a conflict.
Update rate	The frequency at which information is received from the component in run-time	Measured in run-time	Utilized to assign adaptive separations around the bodies

Table 4-1: Common attributes of a component

All attributes of a component are not always common for all of its bodies and joints. Different bodies of the same component are not always identical as well as the different joints. In contrast to the attributes in Table 4-1, components have body-specific attributes, which describe the physical characteristics and interactions of bodies with the environment. Table 4-2 lists the body-specific attributes of a component and introduces their content, method of acquisition, and relevance to the collision avoidance system.

	Content	Acquisition	Relevance
Static volume representation	Simplified representation of the shape of the body in order to achieve faster computation and real-time performance.	Explained in Section 4.1.2.	Utilized in run-time to assign separations and detect conflicts.
Comfort distances	Minimum and maximum comfort distances around each body	Clinical observations, validated by two interventional radiologists	Utilized to assign separation around each body
Exclusivity table	Desired interactions of the body with certain other bodies in particular use-cases	User-defined	The proximities of these bodies during these use-cases are not detected as conflicts.

Table 4-2: Body-specific attributes of a component

Similar to the bodies, different joints of a component have dynamic behavior. Joint-specific attributes of component are used to represent the dynamic characteristics. Table 4-3 lists the joint-specific attributes of a component and introduces their content, method of acquisition, and relevance to the collision avoidance system.

	Content	Acquisition	Relevance
Worst-case braking distance	Worst-case braking distances of all joints in the same order as the kinematic hierarchy	Based on the datasheet of commercially available components and laboratory measurements	Utilized to assign separation around the associated bodies.
Maximum velocity	Maximum expected velocities of all joints of a component in the same order as the kinematic hierarchy	Based on datasheets of commercially available components and laboratory measurements	Utilized to assign separation around the associated bodies.
Uncertainty	Buffer, reserved for the worst-case quantification error associated with each joint	Based on datasheets of commercially available components and laboratory measurements	Utilized to assign separation around the associated bodies
Actual joint value	Value of the joint at the time of quantification	Self-quantifying components report by themselves; a tracking modality reports the values of other components.	Utilized to update the digital twin
Instantaneous joint velocity	Velocity of the joint at the time of quantification	Computed by referring to succeeding signals on actual joint values	Utilized to assign adaptive separations around the bodies.

Table 4-3: Joint-specific attributes of a component

4.3.1.2 Computation of Base Transformation

The implemented solution assumes that the local coordinate centers of components do not move in the run-time. In case of motion, the associated coordinate system must be re-registered to the common coordinate system. The digital replication of the environment after coordinate center registration is visualized by means of a mixed reality simulator; the room composition, kinematic configuration, and the base transformations of the included components are visually checked with the help of VTK Visualization Toolkit [52].

Step 1

Registering the components to the global coordinate system

For all components C^n

Inputs:

- R, 3D coordinates of the markers in component's local coordinate system
- T, 3D coordinates of the markers in global coordinate system

Output:

- BT^n, base transformation of the component coordinate system with respect to the global coordinate system as given by Equation 4-6.

Remarks

- Having all components registered to the global coordinate system, any body can be related to all other bodies in the environment. Distances between all body pairs can be computed.
- Base transformation of a component is assumed to be constant in run-time; thus, it is assumed that the base of a component does not move.

4.3.1.3 Digital Twin of the Therapy Suite

For any given kinematic configuration and base transformation of a component, 3D coordinates of any point of the component can be computed with respect to the global coordinate system. DRU forms the preliminary digital twin of the therapy suite by matching the static volume representations of the bodies to their parent joints and locating the components in the global coordinate system.

Step 2

Build the preliminary therapy suite

For all components C^n

Input:

- Denavit-Hartenberg parameters
- Static volume representations of the bodies $\{[\vartheta_m^n(r_m^n, p_m^n|_{BCS})]_{m=1}^M\}$
- Kinematic configuration Ψ^n
- Base transformation BT^n

Output:

- Static volume representation of the component in the global coordinate system, $\{[\vartheta_m^n(r_m^n, p_m^n|_{GCS})]_{m=1}^M\}$

Remarks

- Distribution of the components in the therapy suite and their postures are obtained.
- The system is aware of the volume in the therapy suite, occupied by the components.
- Components and their bodies can be located relative to the bodies of the other components.

DRU refers to the component database and complements the room composition with the characteristics of the components. Use-cases of the components, comfort distances around the bodies, desired and undesired proximities of body pairs, as well as the worst-case braking distances and maximum velocities of the joints, are mapped to the therapy suite. As a result, a comprehensive digital twin of the therapy suite, with the distribution of components in the environment and their physical and dynamic characteristics, is formed.

4.3.2 Central Registration Unit

Central Registration Unit is the interface of the digital twin to the components. It accepts connection requests of components to the system. It continuously receives the update information from them in run-time and registers all the information coming from different sources, and feeds into the digital twin in run-time. The CRU is characterized to be a TCP/IP server; it waits for the connection requests of the components, which are characterized to be TCP/IP clients, at a previously specified port.

The C-arm, patient table, and assistant robot have potentiometers at their joints, which quantify the actual joint values. They further have computers equipped with TCP/IP infrastructure. Therefore, these components can quantify their postures and transmit this information to the CRU in run-time. On the contrary, human-beings and human-driven components neither can quantify their joint values, nor they can directly access CRU via the TCP/IP interface. A quantification modality is utilized as an intermediary agent to interface these non-self-quantifying components to the CRU server. It can quantify the transformation of a body with respect to its local coordinate system and deliver this information to the CRU via its TCP/IP client. How components are interfaced with the CRU, based on their quantification characteristics, is shown in Figure 4-12.

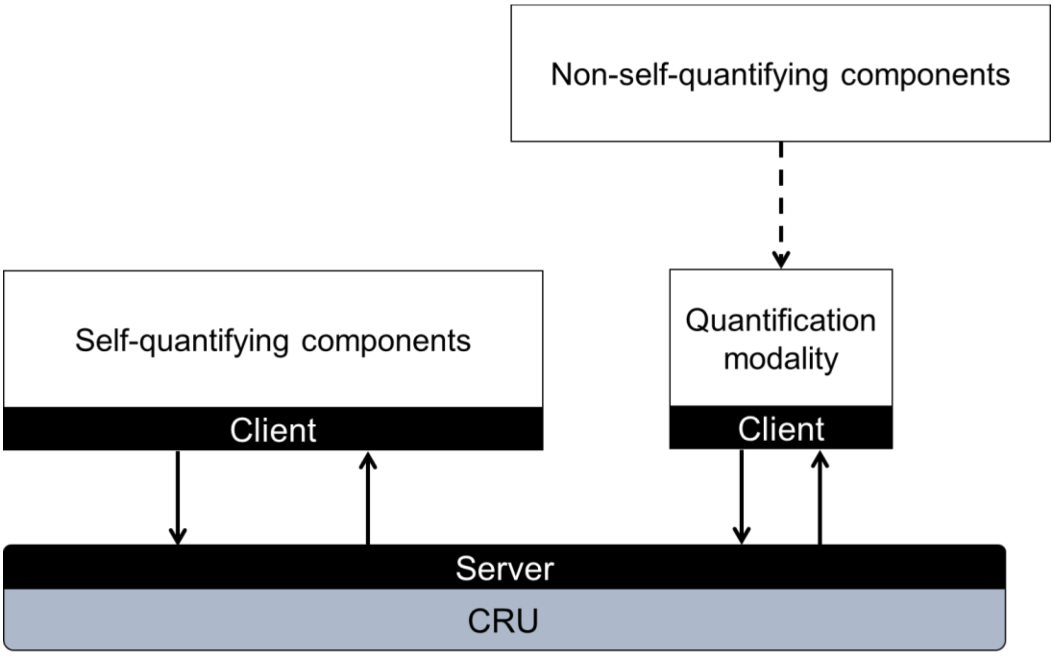


Figure 4-12: Interfacing components to the CRU

4.3.2.1 Connection

Having the IP address and the corresponding port number of the CRU stored in the database, each component client establishes the first connection to the CRU server, reporting in run-time that it is up and running.

After receiving a connection request, the CRU fetches the associated information in the component database and makes a consistency check of the provided information. In case of connection confirmation, the CRU assigns a unique identification number to the connecting component. If the provided information is not consistent, an error message is delivered to the connecting client.

Following a successful connection, the CRU adds the component to the connected components list, registers the dynamic data of the component to the database, and returns a confirmation signal to the client with the assigned identification number.

Step 3

Connecting a component to the CRU

For all components C^n

Input:
- Component name as stored in the database,
- IP address and listener port,
- Base transformation BT^n,
- Kinematic configuration of the component at the time of connection request
- Use-case of the component at the time of connection request.

Do:
- Check if
  - The provided kinematic configuration agrees with the degree-of-freedom information stored in the database,
  - The provided use-case is listed in the database,
  - The provided base transformation is a 4x4 matrix as in the desired form.
- Assign an identification number for the component if all checks have passed. Send the

Output:
- Confirmation signal to the client of the component, including the identification number, in case of a successful check. The component is live in the digital twin.
- Rejection signal to the client of the component in case of an unsuccessful check.

4.3.2.2 Update

While continuously updating, components transmit update signals to the collision avoidance system in case of a posture and use-case change, -irrelevant whether there is a change or not- can also be handled. In both scenarios, the system always has up-to-date information on the components' postures. The update rates of components may differ from each other. There is no limitation or specification related to update rates in this version of the collision avoidance system.

Step 4

Updating component information in the CRU

For any components C^n, which

- Moved, i.e., its posture has changed, or
- Its use-case has changed.

Input:

- The ID number of the component,
- The joint values at the time being,
- The use-case of the component at the time being.

Do:

Compute the update rate of the signals.

Output:

Updated digital twin with

- Actual kinematic configuration $\Psi^n(t)$
- Actual update rate,
- Actual use-case

Remarks

In contrast to the DRU, CRU is an online functional unit; it performs in run-time. The input provided to the CRU as well as the output of the CRU are time varying.

4.3.3 Perception Unit

The components in the therapy suite are mostly self-aware; they do not necessarily know where the other components are and in which use-case they are in.

The Perception Unit receives the run-time information from the components through the CRU and computes the instantaneous velocities of all joints as well as the update rates of the components. It combines this dynamic information with the static information of the components in the database and continuously keeps the digital twin of the therapy suite up to date. It generates overall awareness of the locations, postures, and use-cases of all connected components with a certain amount of latency.

Step 5

Maintain the digital twin of the therapy suite

For each incoming Connection signal of the component C^n

- Activate the corresponding component in the computations,
- Update the component database with
  - Base transformation BT^n
  - Actual kinematic configuration $\Psi^n(t)$
  - Actual use-case

For each incoming Update signal

- Compute the instantaneous velocities of the joints
- Update the component database with
  - Actual kinematic configuration $\Psi^n(t)$
  - Instantaneous joint velocities $\vec{V}^n(t)$
  - Actual use-case
  - Actual update rate

Remarks

- By combining the run-time information, flowing from the CRU, with the static data stored in the database, PU is continuously aware of the environment and the processes:
  - Physical distributions of the components in the room, described by the base transformations,
  - Postures of the components, described by the kinematic configurations,
  - The instantaneous velocity of each joint, computed by the difference in the joint values between two succeeding perceptions,
  - Latency values corresponding to each component,
  - The braking distance of each joint,
  - Measurement uncertainty of each joint,
  - Use-case of each component,
  - The update rate of each component.
- The digital twin is ready for separation assignments and conflict detections.

The VTK-based virtual reality simulator is used in run-time. The update signals are immediately visualized, the consistency of the perception with the reality has been progressively checked.

4.3.4 Separation Assignment Unit

Having an up-to-date digital twin of the environment and global awareness about the environment, the Separation Assignment Unit computes the corresponding volume representations of the components. Any dynamic component has a time-varying point distribution and time-varying radii around those points.

The Kinematic Continuous Collision Detection (KCCD) library, introduced by Frese et al. at [53], is utilized for computing the separation distances around the moving bodies as well as detecting conflicts between components of the therapy suite in run-time. KCCD is an algorithm basically developed to detect the self-collisions of industrial and humanoid robots [22]. It is applied to and tested with German Aerospace Center's (DLR) humanoid robot Justin: It catches two simultaneously thrown balls; KCCD prevents Justin to collide with itself [53]. In the context of this study, the approach introduced by KCCD has been extended to multiple components.

KCCD is preferred to meet the online separation assignment requirements of the therapy suite due to the fact that it functions in real-time and necessitates no *a priori* movement information. It is velocity adaptive in its core essence. Nevertheless, it has been extended to make the algorithm update-rate adaptive and use-case adaptive.

Perception of a component is not in the scope of the KCCD. The PU, based on the input from components via CRU, provides the perception to the KCCD. While the algorithm is developed to prevent the collisions of a single component in itself, self-collisions are not of primary concern of the therapy suite collision avoidance system; it instead focuses on the collisions between different components. The DRU extends this single-component perspective of the KCCD to multiple components by registering all components to a single global coordinate system.

4.3.4.1 Computation of the joint intervals

The SAU administers KCCD algorithm to compute the intervals for any provided perception by the PU. The method on the computation of the joint intervals is described in detail [22].

Step 6

Computing the velocity-adaptive joint intervals

For each incoming Update signal of component C^n

Input:

- Actual kinematic configuration of its joints $\Psi^n(t)$
- Instantaneous velocities of its joints $\vec{V}^n(t)$
- Uncertainty of each joint (constant, read out from the database)
- Braking distance of each joint (constant, read out from the database)
- Latency of the component (constant, read out from the database)

Do:

Feed input to the KCCD algorithm.

Output:

- Intervals of all joints

$$\Phi^n_{velocity}(t) = \{[\eta^n_l(t)]^L_{l=1}\}$$ **Equation 4-14**

Remark

The computed joint intervals are velocity adaptive, but the intervals are not yet adapted to the update rate of a component.

In order to ensure safety, the computed velocity-adaptive joint intervals are enlarged with respect to the update rate of the component as given in Equation 4-11.

Step 7

Computing the update rate-adaptive joint intervals

For each computation of joint intervals for a component C^n

Input:

- Instantaneous velocities of its joints $\vec{V}^n(t)$
- Intervals of the joints, computed by the KCCD algorithm $\Phi^n_{velocity}(t)$
- Duration between the two succeeding update signals of the component $\Delta u^n(t)$, provided by the PU.

Do:

Recompute the joint intervals due to the update rate of the component, $\delta^n_l(t)$, as given by Equation 4-10.

Output:

- Intervals of all joints $\Phi^n(t)$

Remarks:
The resulting intervals of all joints of the component, $\Phi^n(t)$, are adapted to the instantaneous velocities of the joints as well as to the update rate of the component at the time being.

4.3.4.2 Computing the volume representations of dynamic components:

The KCCD algorithm does not only check collisions at the given kinematic configurations but along the whole joint intervals. It sweeps the static volume representation of the body along with the interval of its parent joint. Sweeping a body b_m^n around a joint j_m^n is basically placing the static volume representation ϑ_m^n at I discrete values of the joint between its interval $[\mu_l^n(t),\ \eta_l^n(t)]$. The magnitude of I is specified by the user depending on the computational budget. KCCD takes one step further and computes the entire swept volume representation of a dynamic component. It takes kinematic hierarchy of the component into account, successively includes the sweeping effect of a joint to the preceding bodies [53].

Step 8

Computing the swept volume of a component

For each component C^n

Input:

- Static volume representations of the component, $\{[\vartheta_m^n(r_m^n, p_m^n|_{GCS})]_{m=1}^M\}$
- Intervals of all joints $\Phi^n(t)$
- Computational budget, I

Do:

Feed the input to the KCCD algorithm and compute the volume representation of the body corresponding to I discrete joint values within its computed joint interval

Output:

Swept volume of the component $\mathcal{C}^n(t)$, in which the volume representation of each body is located at I discrete joint values within the given joint intervals:

$$\mathcal{V}_m^n(t) = \{[\vartheta_m^n|_i(r_m^n, p_m^n|_{GCS})]_{i=1}^I\} \quad \textbf{Equation 4-15}$$

$$\mathcal{C}^n(t) = \{[\mathcal{V}_m^n(t)]_{m=1}^M\} \quad \textbf{Equation 4-16}$$

4.3.4.3 Computing the dynamic separation distance around each body

Computation of swept volume of the component is velocity-adaptive and the resulting swept volume $C^n(t)$ is sufficient to ensure the safety in the therapy suite. Nevertheless, it ignores the human-comfort and use-cases of the components. $C^n(t)$ is grown by assigning dynamic separation around the bodies to make the system use-case adaptive as well as to ensure human comfort.

Step 9

Computing the dynamic separation distance around a body

For each computation of $\vartheta_m^n|_i(r_m^n, p_m^n|_{GCS})$

Input:

- Minimum comfort distance of the body, $d_{minComfort}{}_m^n(t)$ (constant, read out from the database)
- Actual use-case of the component C^n as given in the Update signal
- The separation around the body corresponding to the use-case, $d_{useCase}{}_m^n(t)$ (constant, read out from the database)

Do:

Compute the corresponding separation distance around $\vartheta_m^n|_i$ as given in the Equation 4-13.

Output:

- Separation distance around the body, including the influence of its comfort distance and the use-case, $d_{separation}{}_m^n(t)$

Remarks:

- The swept volume as well as the dynamic separation distance of each body of all connected components in the therapy suite are computed.
- Swept volume representation of a component is time-varying so that it adapts to the instantaneous velocities of the joints and the update rate of the component.
- The computed separation distance around a body is dynamic so that it adapts to the use-case of the component as well as it ensures human comfort.

4.3.5 Conflict Detection Unit

Conflict Detection Unit computes the distances between bodies. The KCCD algorithm is utilized to compute the distances between the swept volumes around all body pairs based on a GJK implementation [53]. If the distance between the swept volumes of two bodies is less than or equal to their total separation distances, these bodies are in conflict.

The angiography system, patient table, and the assistant robot in our therapy suite setup are self-aware; they avoid self-collisions by themselves. On the other hand, human-beings, monitors, and trolleys are assumed to have unique rigid bodies. Therefore, detecting self-collisions of individual components is not a requirement in the context of this study. Computation of distances between bodies of the same component is neglected since it reduces the numerical problem and shortens computation time. However, when detecting the conflicts between the bodies of the same component is required, the implemented solution can accomplish self-collision detection without changing any method.

As the PU can receive update signals from multiple components in run-time and the SAU assigns separations around the bodies for any given perception, the CDU can detect the conflicts between multiple components at any time instance. It progressively checks the distances between all body pairs of all components. This essence of the algorithm allows instantaneous movements of components, meaning that conflicts between concurrently moving components can be detected.

If the computed distance between two components is critical, i.e., less than or equal to the summation of the individual separation distances of the bodies at the time, the CDU checks if this pair is listed in the exclusivity table. If the pair is not listed as a desired proximity, these two bodies are in conflict.

Step 10

Measuring distances between body pairs

At each update of the digital twin, for each body pair b_m^n and b_v^y:

Input:

- Swept volume representations of the bodies $\vartheta_m^n|_i(r_m^n, p_m^n|_{GCS})$ and $\vartheta_v^y|_j(r_v^y, p_v^y|_{GCS})$
- The separation distances around the bodies at the time being ${d_{separation}}_m^n(t)$ and ${d_{separation}}_v^y(t)$

Do:

Compute the minimum distance $d(t)$ between the bodies by utilizing the KCCD algorithm.

If $d(t)$ is critical, check if the proximity of the bodies is desired.

Output:

If the distance between the bodies is critical and the proximity is undesired, identities of the conflicting components and bodies:

- C^n and C^y
- b_m^n and b_v^y

Remarks:
Undesired proximity of two bodies is detected in a timely manner so that proper actions can be taken to prevent collisions. Detection is achieved so that the instantaneous velocity, update rate, and the use-cases have been influential in the detection process.

In order to differentiate the desired and undesired proximities, the CDU refers to the exclusivity table in the static component database. It reads out the use-cases of the components at the time being and searches for these use-cases in the exclusivity table.

4.3.6 Conflict Resolution Unit

When a conflict is detected, the CDU reports the conflicting bodies to the Conflict Resolution Unit. The CResU refers to the types of the conflicting components as well as their use-cases at the time being and takes proper measures to avoid collision between these two bodies. The CDU detects and reports multiple conflicts in the entire therapy suite at a given time point, and the CResU acts to resolve all concurrent conflicts.

If at least one of the conflicting components is in a use-case, for which the proximity of the two bodies is explicitly listed as a desired interaction, these components are *under observation*. Otherwise, the components are in *undesired interaction*. In both cases, the CResU sends feedback to these components via CRU. CRU then intervenes with the conflicting components according to their types.

Velocity-adaptive Conflict Resolution

The user can activate the setting of velocity-adaptive collision avoidance. In this case, the SAU multiplies the joint intervals and radii by a factor of 2, resulting in larger swept volumes around the components. Accordingly, the CResU does not immediately trigger the full-stop feedback; it instead sends a slow-down feedback to the motorized components and marks the conflicting components as under observation. Slowing down results in a smaller swept volume around the moving component:

- If the conflict persists in the next cycle despite the smaller swept volume, and the distance between the conflicting components is still more than the minimum separation distance, the component continues its motion. This approximation is allowed at a limited velocity and under the observation of the operator.
- If the distance between the components under observation reaches the minimum allowed separation, that means the summation of the minimum separation distances of the conflicting components, the stop signal is triggered.

The online decision-making chart is visualized in Figure 4-13. The motivation for the velocity-adaptive collision avoidance approach is to minimize the number of stop commands and allow the components to continue their motions towards their target at a lower velocity. The components can span larger space without interruption, and the agility of the system is increased.

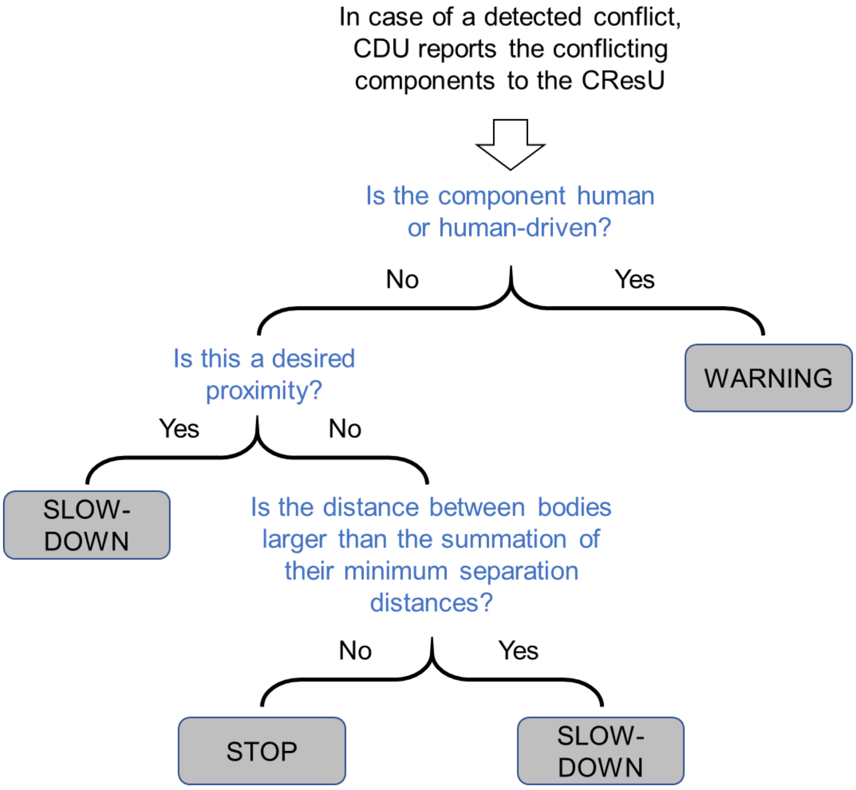


Figure 4-13: Velocity-adaptive conflict resolution approach

5

Evaluation

The implemented collision avoidance system, as described in Chapter 4, is evaluated in terms of meeting the requirements of a contemporary therapy suite. The purpose of the evaluation is to verify if the solution is capable of preventing collisions without blocking collaborative interactions. Consequently, the implemented solution is tested in a real experimental environment to check if safety, agility, and human comfort are ensured.

Influence of velocities, use-cases, and update rates of the components on safety, agility, and human comfort are observed in the experiments. Separations between components at critical time instances are computed. Spatial Agility, Human Comfort, Mismatch Assignment, and Temporal Agility Scores of the implemented collision avoidance system are evaluated in different test setups.

Section 5.1 describes tests and their context. Section 5.2 introduces the parameters measured in the tests and how the performance of the system in these tests is evaluated. The experimental setup is introduced in Section 5.3. The measured critical values as well as how they are obtained are given in Section 5.4. Performance of the system in the experiments is evaluated in Section 5.5, while the results are interpreted in Section 5.6.

5.1 Experimental Scenarios

The capability of the programmed collision avoidance system to prevent the undesired proximities between the major components of the contemporary therapy suite is tested in various scenarios. Within the first and second scenarios, the validity of the overall solution approach in static and dynamic obstacle situations is checked. Within the third and fourth scenarios, influences of the update rate and velocity on spatial agility and human comfort are tested. Finally, the velocity-adaptive conflict resolution method is tested and its influence on the temporal agility is checked in the fifth scenario. Evaluation experiments are classified into the following 5 types:

Type 1 – Avoiding collisions with static obstacles:

- The expected result of the Type 1 experiments is that the implemented solution prevents all catastrophic or critical collisions as described in Requirements Analysis and shown in Table 2-2. In these experiments the following aspects have been verified:
    - Whether the digital replication method is capable of representing the physical and dynamic characteristics of the components,
    - If the separation assignment method achieves safe separation of bodies,
    - Whether the conflict detection method detects in time undesired vicinities,
    - If conflict resolution method prevents collisions before they occur.
- The reaction of the system to stationary obstacles has been tested by introducing specific component pairs and by moving the component-of-interest towards the obstacle with the intention of provoking a collision.
- The staff members and human-driven components can continue their movements even after the audio warning of the CResU. For the sake of reliability of the performance computations, these components are characterized only as static obstacles.
- Use-cases and the update-rates of the components during Type 1 tests did not change; the velocity-adaptive conflict resolution mode was deactivated.
- Table 5-1 lists the tested component pairs, of which the obstacles were stationary.

Component -of-interest	Static obstacle
C-arm	Patient
C-arm	Trolley
C-arm	Staff member
Assistant robot	Patient
Assistant robot	Patient table
Assistant robot	Trolley
Assistant robot	Staff member
Patient table	Staff member
Patient	C-arm
Patient table	Trolley

Table 5-1: Component pairs, used in Type 1 experiments, consisting of a dynamic object-of-interest and a static obstacle

From the data acquisition, virtual representation, computation, and resolution perspectives, “assistant robot – the patient table” pair is identical to the “assistant robot – patient” pair. Similarly, the “C-arm – monitor” and “assistant robot – monitor” pairs are identical to the C-arm – trolley and the assistant robot – trolley pairs. To avoid redundancy, the “assistant robot – patient table”, “C-arm – monitor”, and “assistant robot – monitor” pairs are not included in the experiments.

Type 2 - Avoiding collisions with dynamic obstacles:

- Expected result of Type 2 experiments is that the implemented solution is capable of handling concurrent movements of components. In contrast to Type 1 experiments, the capability of the overall solution on avoiding collisions in case of dynamic obstacles is verified.
- In order to precisely measure the conflict resolution performance of the collision avoidance system, the test pairs are limited to motorized components in order to be able to reproduce the results.
- Both components moved independently of each other.
- Use-cases and the update-rates of the components did not change; the velocity-adaptive mode was deactivated.
- Table 5-2 lists component pairs, wherein the obstacles are dynamic.

Component -of-interest	Dynamic obstacle
C-arm	Assistant robot
Patient	Assistant robot

Table 5-2: Component pairs, used in Type 2 experiments, consisting of concurrently moving components

Type 3 – Adapting to update rates:

- Responsiveness of the system to the update rates of components has been tested, specifically with the pair “dynamic assistant robot and static patient”. Improvement on the agility is expected as the update rate increases.
- The velocity-adaptive conflict resolution was disabled in Type 3 tests.
- Table 5-3 lists the tested update rates of the assistant robot.

Component -of-interest	Update rate of the object-of-interest	Static obstacle
Assistant robot	1 Hz	Patient
Assistant robot	10 Hz	Patient
Assistant robot	25 Hz	Patient
Assistant robot	40 Hz	Patient
Assistant robot	50 Hz	Patient
Assistant robot	60 Hz	Patient
Assistant robot	75 Hz	Patient
Assistant robot	90 Hz	Patient
Assistant robot	100 Hz	Patient

Table 5-3: The pair “dynamic assistant robot and stationary patient” has been tested at different update rates of the assistant robot

Type 4 – Adapting to use-cases:

- In Type 4 experiments, the responsiveness of the system to the use-cases of the components has been tested.
- Expected result of the Type 4 experiments is that for each use-case, the implemented solution achieves conflict detection in compliance with the desired separation of the conflicting bodies.

- The assistant robot, C-arm, and patient are pairwise used to test the system response in different use-cases, as shown in Table 5-4.
- The velocity-adaptive mode was deactivated in Type 4 tests as well.

Component -of-interest	Use-case of the assistant robot	Static obstacle
Assistant robot	Needle attached	Patient
C-arm	Needle attached	Assistant robot
Assistant robot	Needle insertion	Patient
C-arm	Needle insertion	Assistant robot

Table 5-4: In Type 4 experiments, the “dynamic assistant robot and stationary patient” pair was tested in two different use-cases of the assistant robot

The assistant robot has different minimum comfort distance values at different use-cases. In the context of Type 4 experiments, the end effector of the robot is exposed to conflicts. The end effector’s minimum comfort distances in the two use-cases are shown in Table 5-5.

Component -of-interest	Use-case of the assistant robot	Static obstacle	Minimum comfort distance of the robot’s end-effector
Assistant robot	Needle attached	Patient	150 mm
C-arm	Needle attached	Assistant robot	250 mm
Assistant robot	Needle insertion	Patient	10 mm
C-arm	Needle insertion	Assistant robot	350 mm

Table 5-5: Type 4 experiments with various component pairs, tested in two different use-cases of the assistant robot

The robot’s minimum comfort distance does not only depend on its use-case but also on the conflicting component. The robot is allowed to approach closer to the patient in needle insertion mode, while the proximity of the C-arm to the assistant robot is not permitted. This is why the end effector of the robot has two different minimum comfort distances in needle insertion use-case.

Type 5 – Adapting to instantaneous velocities:

- Expected result of Type 5 experiments is that the velocity-adaptive conflict resolution leads to high spatial agility, thereby allowing components to move faster.
- Impact of the instantaneous velocity on conflict resolution has been tested by rotating the C-arm towards the stationary trolley at two different velocities. The higher velocity of the C-arm is set to 100°/s, and the lower velocity is set to 20°/s. Furthermore, the impact of the velocity-adaptive approach on spatial agility and temporal agility has been tested by enabling and disabling the velocity-adaptive conflict resolution mode, which is described in Section 4.3.6.
- Table 5-6 lists combinations in which the measurements have been carried out. In all tests, the C-arm started its motion from the same kinematic configuration, while the trolley was fixed.
- Both components had fixed use-cases and update-rates throughout the tests.

Component-of-interest	Velocity-adaptive mode	Static obstacle
C-arm, low-velocity	Deactivated	Trolley
C-arm, high-velocity	Deactivated	Trolley
C-arm, low-velocity	Activated	Trolley
C-arm, high-velocity	Activated	Trolley

Table 5-6: Impact of instantaneous velocity on conflict detection and the impact of velocity-adaptive mode on conflict resolution have been tested in focus of the Type 5 experiments. Focus has been the “C-arm and trolley” pair.

The components moved with no *a priori* trajectory information throughout all tests, their movement paths were not known to the collision avoidance system and the obstacle.

5.2 Critical Parameters and Evaluation Criteria

Throughout the experiments, the distances between the conflicting bodies have been measured at the instances of conflict detection and resolution. These critical distances are d_{det} and d_{final}, respectively, as described in the Section 2.2:

d_{det}: Distance between the conflicting bodies at the time of conflict detection

d_{final}: Distance between the conflicting bodies at the time of conflict resolution, i.e., when both bodies came to a complete stop.

For each test case, the user-defined minimum and maximum allowed comfort distances between the test pairs are also provided for the performance evaluations. Recalling from Equation 2-1 and Equation 2-2 in Section 2.2:

d_{max}: Summation of the maximum allowed comfort distances of the conflicting bodies. The distance between the bodies at the instant of conflict detection, d_{det}, cannot exceed this value.

d_{min}: Summation of the minimum comfort distances of the conflicting bodies. The bodies cannot get closer than this value at the end of conflict resolution; the distance between the bodies at the time of conflict resolution, d_{final}, cannot be less than this value.

Maximum and minimum allowed comfort distances of all individual components are given in Section 5.3.2.

The distances between bodies at the critical instances are depicted in Figure 5-1. As exemplary components, the C-arm and assistant robot have been shown.

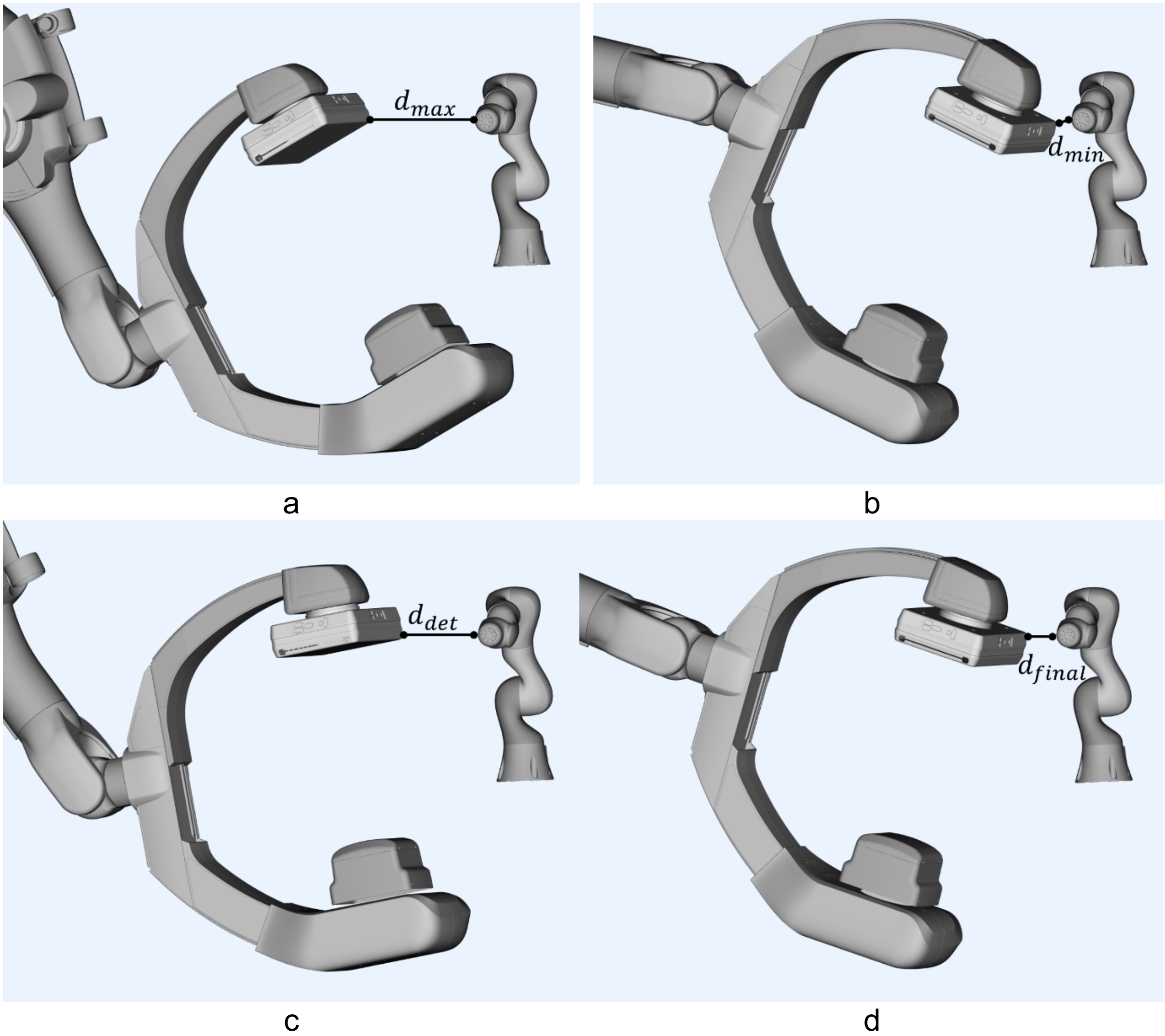
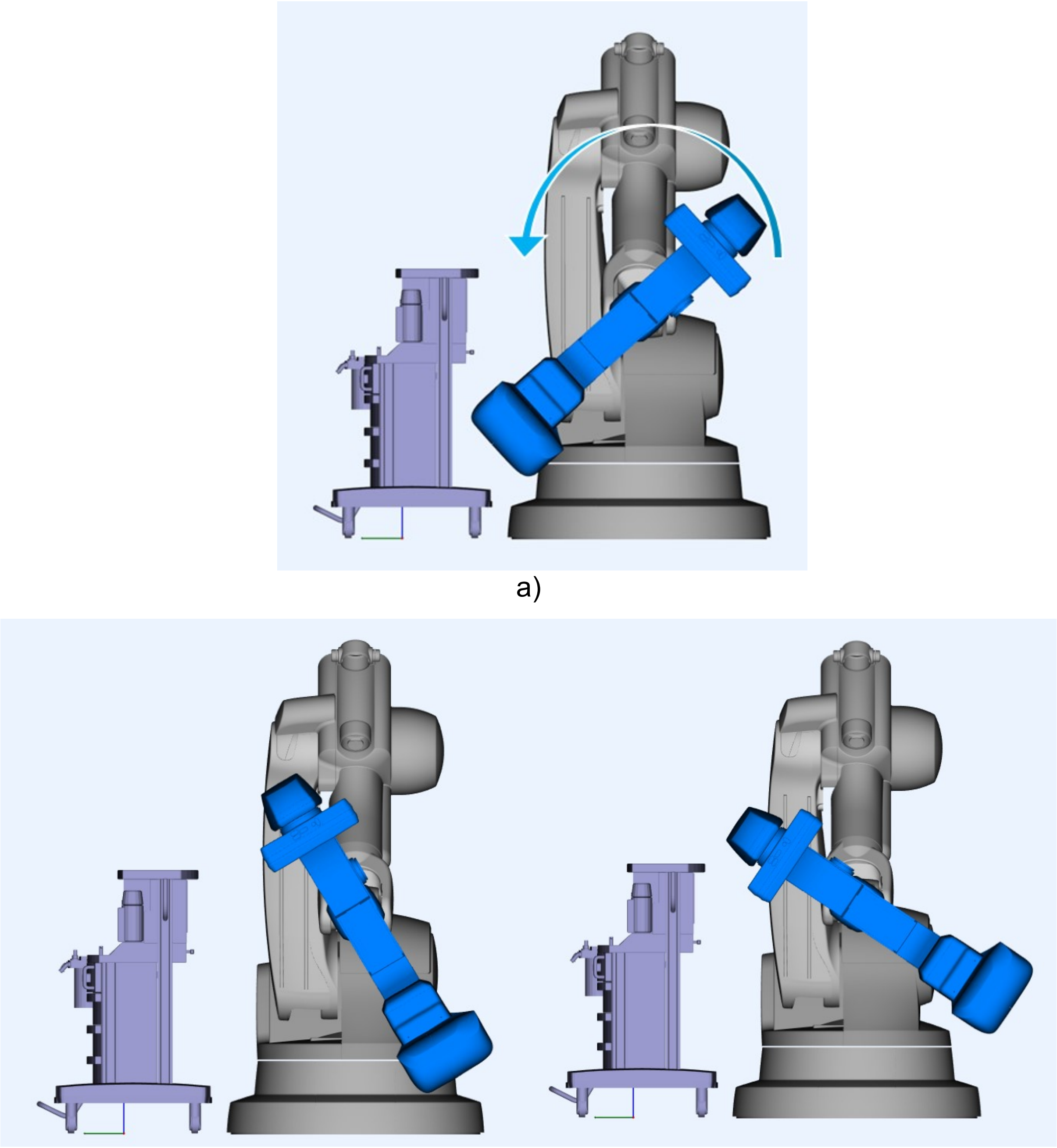


Figure 5-1: Critical distances between bodies. a) Maximum allowed separation distance between conflicting bodies. b) Minimum allowed separation distance between conflicting bodies. c) Distance between the bodies at the instant of conflict detection. d) The distance between the bodies at the end of conflict resolution.

In contrast to the other types of tests, total travel duration of the component-of-interest from a certain starting position to the fixed obstacle has been measured within the Type 5 tests. Figure 5-2 (a) depicts the starting configuration of the C-arm towards the fixed trolley. (b) and (c) depict the final configuration of the C-arm, corresponding to the fast and slow travels, respectively.



a)

b) c)

Figure 5-2: Depiction of the starting position of the C-arm in Type 5 tests. C-arm rotates as depicted by the arrow and approaches to the stationary trolley at two different velocities. b and c visualize the configuration of the C-arm at the end of conflict resolution corresponding to the fast movement and the slow movement, respectively.

The overall performance of the system has been evaluated based on the corresponding spatial and temporal agility, mismatch assignment, and human comfort scores. These performance metrics altogether indicate how safe and collaborative the developed collision avoidance system is:

- The Spatial Agility Score reveals the conflict detection performance of the system. For a given component pair, this score indicates how ample the physical operating space the system allows those components. As explained in Section 2.6, the Spatial Agility Score is a function of d_{det} as well as the allowed minimum and maximum comfort distances between the conflicting bodies. Smaller d_{det} indicates that the system allows the components to get closer to each other until it alerts for a collision risk. For a given set of minimum and maximum comfort distances of the bodies, smaller d_{det} results in higher spatial agility. Therefore, in the range of 0% and 100%, a higher Spatial Agility Score implies that the collision avoidance system allows larger physical operating space to the components. A Spatial Agility Score higher than 100% implies the system is not capable of detecting conflicts on time. In such a case, physical safety is not ensured.
- The Temporal Agility Score implies how fast or slow the object-of-interest in a particular interaction was. For a given component pair, shorter travel duration of the object-of-interest from a specific starting point to the static obstacle implies higher Temporal Agility Score. In Type 5 tests, the C-arm has been driven from the same starting point to the fixed trolley at two different velocities, duration of the travel until the C-arm came to a complete stop has been measured, the Temporal Agility Score has been computed relatively.
- The Mismatch Assignment Score reveals the conflict resolution performance of the system. This score relates the d_{final} to the d_{min} between conflicting pairs; the more d_{final} approximates d_{min}, the higher the Mismatch Assignment Score is. In the ideal case, d_{final} is equal to d_{min}. Nevertheless, due to the differences between the assumed and realized values of the physical constraints like the measurement uncertainties and latency, this equality cannot be achieved. A lower Mismatch Assignment Score implies that the relevant assumptions can be further improved. Any interaction where $d_{final} < d_{min}$ must be analyzed separately, as safety hazards have been introduced.
- The Human Comfort Score signals if the conflict detection and resolution were performed within the user-defined comfort range. If the system detects a conflict between two bodies outside of their maximum allowed comfort zone, that means $d_{det} > d_{max}$, the system interferes with the user comfort, and the

Human Comfort Score is 0. On the contrary, if the distance between the bodies at the time of conflict resolution is less than the minimum comfort distance, i.e. $d_{final} < d_{min},$ the system induces safety risks and the Human Comfort Score is -1.

5.3 Experimental Setup

All tests have been carried out in an experimental intervention room, equipped with an angiography system (Artis zeego, Siemens Healthineers GmbH) and an assistant robot (LBR iiwa 14 R820, KUKA Roboter GmbH). A ceiling-mounted monitor has been utilized as a generic ceiling-mounted component and a trolley has been utilized as a generic trolley-based component. A phantom represented the patient and a staff member. Components, which are not self-quantifying, have been tracked by using an optical tracking system (Polaris Electra, NDI). The experimental setup is shown in Figure 5-3.

Figure 5-3: Arrangement of different components within the experimental intervention room

Artis zeego and the Magnus table are interfaced to the CRU via AXCS-client, which delivers the information of both components to the CRU in run-time. Both components are capable of communicating their kinematic configuration and use-case information to the external world, but they are restricted in terms of getting commands from the external world due to the security reasons. A Test Automation Computer (a specialized testing computer, not permitted to be used in clinical routine) allows sending motion commands to the Artis zeego and the Magnus table. The client of LBR iiwa 14 R820 provides its kinematic configuration and use-case information to the CRU and delivers motion commands to the assistant robot. The Polaris Electra optical tracking system is used to quantify and communicate the location and kinematic configuration of the phantom, ceiling-mounted monitor, and the trolley. Obviously, the optical tracking system cannot reflect motion commands back to these associated components.

5.3.1 Hosting Computers

Two different computers are used to host the functional units of the collision avoidance system due to the fact that some units require Windows and others Linux operating system for functioning. The functional units DRU, CRU, PU, and CResU, as well as the digital twin, are hosted on a computer with Windows 10 operating system, while the SAU and CDU are hosted on a computer with Ubuntu 14 operating system. These computers are located in the same local area network, and they bidirectionally exchange information in run-time via TCP/IP protocols.

5.3.2 Digital replication of the environment

The use-cases, latency, and update rate values are common for all bodies and joints of a component. Besides these common attributes, the same maximum comfort distance is assigned around all bodies of a component. The values of these attributes during the tests are tabulated in Table 5-7:

- Only the C-arm and the assistant robot have use-cases defined. Use-cases of other components are ignored as they are not involved in the use-case tests.
- Latency values are experimentally observed by using the optical tracking system. To ensure safety, worst-case values are assumed.
- Update rate of each component is set by the user during the tests. Only in Type 3 experiments, the assistant robot had different update rates as described in Section 5.1.
- The maximum comfort distances of the C-arm, assistant robot, patient table are identified with respect to the maximum distance they can travel in 1 second. Maximum comfort distances of the monitor, trolley, and person are identified by agreement of two interventional radiologists.

Component	Use-cases	Latency	Update rate	Maximum comfort distance
C-arm	Idle Imaging	60 msec.	6,67 Hz	320 mm
Patient table	NA	60 msec.	6,67 Hz	270 mm
Patient	NA	60 msec.	6,67 Hz	270 mm
Assistant robot	Idle Tooltip attached Tooltip active	20 msec.	10 Hz	250 mm
Monitor	NA	5 msec.	30 Hz	300 mm
Trolley	NA	5 msec.	30 Hz	400 mm
Person	NA	5 msec.	30 Hz	320 mm

Table 5-7: Attributes of the components, required for digital replication

During the experiments, the patient is assumed to be stationary with respect to the table-top, the patient does not change its posture and moves only together with the table-top. No further position and posture information are collected via the optical tracking system. Patient body is represented as an extension to the table-top in the kinematic hierarchy; therefore, the latency and the update rate of the table are applied to the patient during the digital replication.

Each body and joint of a relevant component have not only the common attributes as shown in Table 5-7, but also individual attributes. Latter are listed in Table 5-8. The attribute term “representing points” refers to the amount of points used for generating the SSCH representation of the associated body. Degree-of-Freedom (DOF) describes the number of axes, around which the bodies move. Table-top, monitor, trolley, and human-beings are represented to have unique bodies, which can move around 4 axes: Translation around 3 orthogonal prismatic joints and rotation around 1 revolute joint. The C-arm and the assistant robot are assumed to have fixed bases in run-time; therefore, DOF of their bases are 0. Under the assumption that the patient does not move with respect to the table-top, DOF of bodies associated with the patient are also 0.

Component	Body	Minimum comfort distance	Number of representing points	DOF	Joint type(s)	Maximum instantaneous velocity	Uncertainty	Braking distance
Angiography system	Base	20 mm	9	0	NA	0	0,00 °	0,00 °
	Link 1	20 mm	9	1	Revolute	13 °/s	1,50 °	2,50 °
	Link 2	20 mm	9	1	Revolute	27 °/s	1,50 °	4,00 °
	Link 3	20 mm	9	1	Revolute	33 °/s	1,50 °	4,70 °
	Link 4	20 mm	6	1	Revolute	181 °/s	1,50 °	5,00 °
	Link 5	20 mm	6	1	Revolute	53 °/s	1,50 °	5,00 °
	C-arm 1	20 mm	6	1	Revolute	181 °/s	1,50 °	6,00 °
	C-arm 2	20 mm	18	1	Revolute	181 °/s	1,50 °	6,00 °
	C-arm 3	20 mm	6	1	Revolute	181 °/s	1,50 °	6,00 °
	C-arm 4	20 mm	11	1	Revolute	181 °/s	1,50 °	6,00 °
	C-arm 5	20 mm	7	1	Revolute	181 °/s	1,50 °	6,00 °
	C-arm 6	20 mm	11	1	Revolute	181 °/s	1,50 °	6,00 °
	Detector	20 mm	13	1	Revolute	181 °/s	1,50 °	6,00 °
	Tube	20 mm	9	1	Revolute	181 °/s	1,50 °	6,00 °
Table-top	Unique body	20 mm	4	4	Prismatic	154 mm/s	0,50 mm	15 mm
					Prismatic	54 mm/s	0,50 mm	1 mm
					Prismatic	20 mm/s	0,50 mm	1 mm
					Revolute	25 °/s	0,86 °	3 °
Patient	Head	50 mm	4	0	NA	0	0,86 °	0
	Body	50 mm	6	0	NA	0	0,86 °	0
	Feet	50 mm	3	0	NA	0	0,86 °	0
Assistant robot	Base	50 mm	1	0	NA	0	0,00 °	0,00 °
	Link 1	50 mm	4	1	Revolute	85 °/s	0,86 °	5,74 °
	Link 2	50 mm	4	1	Revolute	85 °/s	0,86 °	6,00 °
	Link 3	50 mm	4	1	Revolute	100 °/s	0,86 °	9,32 °
	Link 4	50 mm	4	1	Revolute	75 °/s	0,86 °	3,16 °
	Link 5	50 mm	4	1	Revolute	130 °/s	0,86 °	5,48 °
	Link 6	50 mm	4	1	Revolute	135 °/s	0,86 °	5,69 °
	Link 7	100 mm	5	1	Revolute	135 °/s	0,86 °	5,69 °
Monitor	Unique body	50 mm	4	4	Prismatic	300 mm/s	0,25 mm	40 mm
					Prismatic	300 mm/s	0,25 mm	40 mm
					Prismatic	200 mm/s	0,25 mm	10 mm
					Revolute	25 °/s	0,57 °	5 °
Trolley	Unique body	50 mm	4	4	Prismatic	400 mm/s	0,25 mm	40 mm
					Prismatic	400 mm/s	0,25 mm	40 mm
					Prismatic	200 mm/s	0,25 mm	10 mm
					Revolute	25 °/s	0,57 °	5 °
Person	Unique body	320 mm	5	4	Prismatic	500 mm/s	0,25 mm	300 mm
					Prismatic	500 mm/s	0,25 mm	300 mm
					Prismatic	500 mm/s	0,25 mm	300 mm
					Revolute	25 °/s	0,57 °	15 °

Table 5-8: Individual attributes of the bodies

Numerical values of the minimum comfort distances have been assigned based on laboratory measurements and a rating of interventional radiologists whether they felt uncomfortable when another component stands closer than 20 mm to the C-arm, even if both components are stationary. The same method is applied to determine the minimum comfort distances of the other components. To simplify computations, a person is not considered as a component-of-interest but as an obstacle only, thereby an identical value has been assigned to the minimum and maximum comfort distances. Laboratory measurements showed that people feel uncomfortable when a dynamic component came closer to them than 320 mm. Therefore, the comfort distance around a person is assumed to be 320 mm.

The local coordinate system of table base is assumed to be the global coordinate system in the therapy suite. Transformations of the assistant robot's and the optical tracking system's local coordinate systems with respect to the global coordinate system are image-based computed, as explained in Chapter 4. The transformation matrix of the angiography system is obtained from the vendor's installation guide. The base rotation, base translation and scaling factor of these components are tabulated in Table 5-9. The monitor, trolley, and the staff member are linked to the global coordinate system through the optical tracking system; the local coordinate center of an optically tracked component is the local coordinate center of the optical tracking system.

	Rotation	**Translation**	**Scale factor**
Assistant robot	$\begin{bmatrix} 0,00493 & 0,99992 & -0,01164 \\ -0,99998 & 0,00497 & 0,00348 \\ 0,00353 & 0,01162 & 0,99993 \end{bmatrix}$	$\begin{bmatrix} -611,90882 \\ 446,32939 \\ 884,54341 \end{bmatrix}$	1
Optical tracking system	$\begin{bmatrix} 0,39828 & -0,26012 & 0,87961 \\ 0,11552 & 0,96554 & 0,23322 \\ -0,90996 & 0,00872 & 0,41461 \end{bmatrix}$	$\begin{bmatrix} 302,03605 \\ 25,36462 \\ 2069,71863 \end{bmatrix}$	1
Angiography system	$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$	$\begin{bmatrix} -4100 \\ 0 \\ 0 \end{bmatrix}$	1
Table-top	$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$	1

Table 5-9: Transformations of the assistant robot, the optical tracking system camera, the angiography system, and the table-top coordinate systems with respect to the global coordinate system

The digital twin has been visualized by the VTK-based mixed reality simulator. Figure 5-4 shows the components and the corresponding digital twin, which are used in the experiments, and their distribution in the environment.

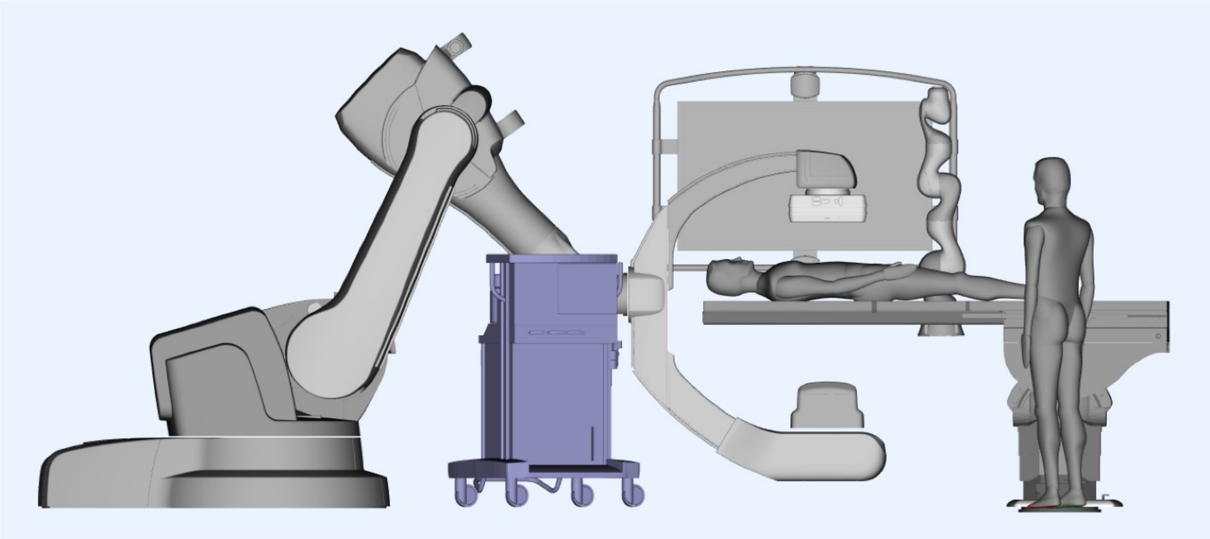


Figure 5-4: Virtual representation of the test components in the experimental setup

Figure 5-5 depicts the kinematic hierarchy of all components. It provides a list of joints in a hierarchical order; it is possible to identify the joints from the proximal to the distal. Furthermore, the connection of all bodies to the relevant joint in the kinematic chain has been shown.

Joints of self-quantifying components are equipped with potentiometers, allowing a digital read-out at any time instance and a reporting to the collision avoidance system. On the contrary, kinematic configuration of other components, namely the people or human-driven components, are quantified and communicated by the optical tracking system.

Having a physical body between two joints is not obligatory; that means two or more joints can be in direct neighborhood without having a physical body in between. On the contrary, multiple bodies can be connected to a single joint. Having the kinematic hierarchy and the transformations of the assistant robot, the optical tracking system camera, the angiography system, and the table-top coordinate systems with respect to the global coordinate system, position and orientation of any body can be related to another body.

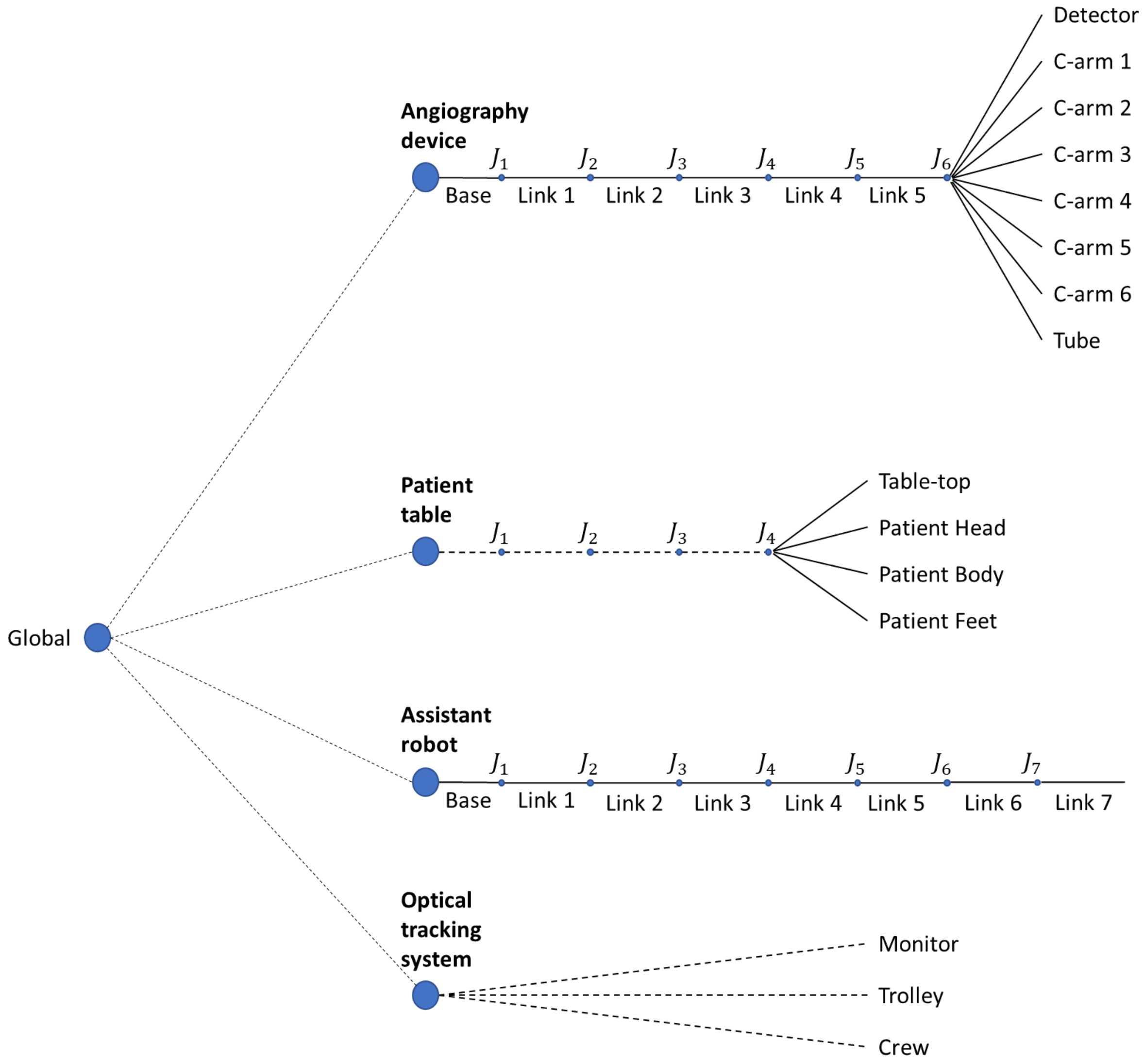


Figure 5-5: Kinematic hierarchy of the relevant components and their interrelation to the global coordinate system

The SSCH representations of test components are shown in Figure 5-6, rendered by the VTK-based mixed reality simulator.

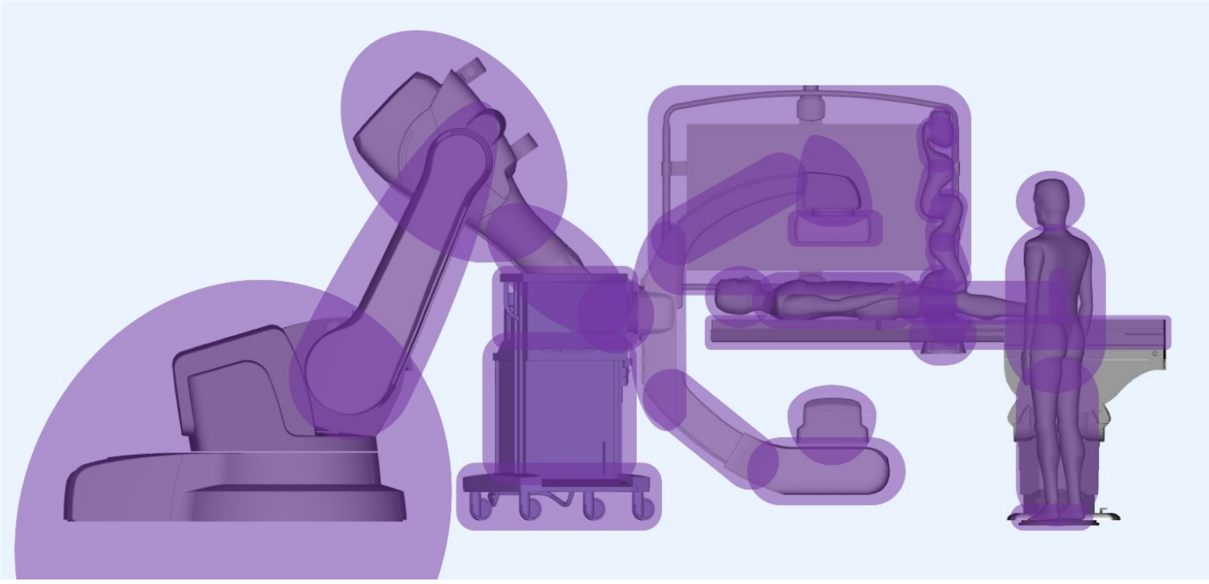


Figure 5-6: SSCH representation of the stationary bodies of the angiography system, table-top, and the assistant robot

5.4 Measurements

In the experiments of all types, the component-of-interest is driven towards the obstacle to provoke a collision. The collision avoidance system detected the conflicts and took the proper actions to resolve the conflicts. The critical distances between the conflicting bodies at the instants of conflict detection and conflict resolution, d_{det} and d_{final}, are computed. These critical distances are required but not sufficient for evaluating the spatial agility, human comfort, and mismatch assignment scores: The total minimum and maximum comfort distances around the conflicting bodies, d_{min} and d_{max}, are also prerequisites for computing these scores.

- d_{det} and d_{final} are obtained during the experiments. They are computed by the KCCD algorithm based on the base transformations and the actual kinematic configurations of the components.
- As the minimum and maximum comfort distances around the bodies are user-defined and constant, d_{min} and d_{max} are not measurements but direct values from the comfort distances of the conflicting bodies (as described in Section 2.2.2 based on the values given in Table 5-7 and Table 5-8).

Specifically, in Type 5 experiments, the duration of the travel, t_{travel}, of a component-of-interest during its movements is measured in order to compute the Temporal Agility Score of the system.

Each test is repeated 5 times to determine the least performance of the system. Since the tests are repeated under controlled conditions, e.g., same velocity of the components in each repetition, results did not show significant differences. Nevertheless, the worst-case values of d_{det}, d_{final}, and t_{travel} are picked to compute the performance scores.

Table 5-10 lists the measured critical distances between the test pairs in Type 1 experiments.

Component-of-interest	Static obstacle	d_{det} (mm)	d_{final} (mm)	d_{min} (mm)	d_{max} (mm)
C-arm	Patient	274	185	70	520
C-arm	Trolley	190	155	70	720
C-arm	Staff member	440	390	340	640
Assistant robot	Patient	183	165	150	450
Assistant robot	Patient table	153	135	120	400
Assistant robot	Trolley	188	162	150	550
Assistant robot	Staff member	452	433	420	570
Patient table	Staff member	369	356	340	470
Patient	C-arm	96	80	70	520
Patient table	Trolley	94	78	70	550

Table 5-10: The critical distances between test pairs in Type 1 experiments

The critical distances between the test pairs in Type 2 experiments are listed in Table 5-11.

Component -of-interest	Dynamic obstacle	d_{min} (mm)	d_{max} (mm)	d_{det} (mm)	d_{final} (mm)
C-arm	Assistant robot	120	570	252	173
Patient	Assistant robot	150	450	225	177

Table 5-11: The critical distances between test pairs in Type 2 experiments

Measured critical distances between the assistant robot and the patient with varying update rates in Type 3 experiments are given in Table 5-12.

Update rate (Hz)	d_{min} (mm)	d_{max} (mm)	d_{det} (mm)	d_{final} (mm)
1	150	450	912	852
10	150	450	324	251
25	150	450	278	193
40	150	450	272	184
50	150	450	268	180
60	150	450	264	176
75	150	450	263	173
90	150	450	261	171
100	150	450	260	170

Table 5-12: The critical distances between test pairs, corresponding to the tested update rates, in Type 3 experiments

The critical distances between the test pairs of Type 4 experiments, corresponding to different use-cases of the assistant robot, are given in Table 5-13.

Component -of-interest	Use-case of the assistant robot	Static obstacle	d_{min} (mm)	d_{max} (mm)	d_{det} (mm)	d_{final} (mm)
Assistant robot	Needle attached	Patient	200	520	234	217
C-arm	Needle attached	Assistant robot	270	570	352	314
Assistant robot	Needle insertion	Patient	60	520	78	64
C-arm	Needle insertion	Assistant robot	370	570	450	409

Table 5-13: The critical distances between the test pairs of Type 4 experiments, corresponding to different use-cases of the assistant robot

Finally, the critical distances between the C-arm and the trolley as well as the duration of the C-arm movement in Type 5 experiments are provided in Table 5-14. The values are obtained at different rotation velocities of the C-arm while the velocity-adaptive conflict resolution is enabled and disabled.

Velocity of the C-arm	**Velocity adaptive mode**	d_{min} **(mm)**	d_{max} **(mm)**	d_{det} **(mm)**	d_{final} **(mm)**	**Duration of the movement (sec)**
Low	Disabled	70	720	171	112	11,8
High	Disabled	70	720	586	297	2,3
Low	Enabled	70	720	171	112	11,8
High	Enabled	70	720	882	112	4,9

Table 5-14: The critical distances between the test pairs and the movement duration of the component-of-interest in Type 5 experiments.

5.5 Performance Evaluation

The Spatial Agility, Mismatch Assignment, and Human Comfort Scores of the implemented solution are computed in response to the measurements of critical distances in Type 1, Type 2, Type 3, and Type 4 experiments. The temporal agility of the solution is computed in the context of Type 5 experiments. The scores are computed as described in Section 2.6 based on the results given in Section 5.4. This section summarizes the resulting scores of all experiments. These results are later analyzed in Section 5.6.

Table 5-15 lists the performance indicators of the system in Type 1 tests, in which the components-of-interest were driven towards a static obstacle. Conflict detection between all test pairs in all test cases has been achieved on time, conflicts are resolved within the given comfort range. Due to the C-arm's fast movements, relatively low update rate, and high safety margins are associated with the assumptions. This resulted in relatively low Spatial Agility as well as Mismatch Assignment Scores for the collision avoidance system.

Component-of-interest	Static obstacle	Spatial Agility Score (%)	Mismatch Assignment Score (%)	Human Comfort Score
C-arm	Patient	55	38	1
C-arm	Trolley	82	45	1
C-arm	Staff member	67	87	1
Assistant robot	Patient	89	91	1
Assistant robot	Patient table	88	89	1
Assistant robot	Trolley	91	93	1
Assistant robot	Staff member	79	97	1
Patient table	Staff member	78	96	1
Patient	C-arm	94	88	1
Patient table	Trolley	95	90	1

Table 5-15: Performance scores of the collision avoidance system in Type 1 tests

Table 5-16 lists the performance indicators of the system in Type 2 tests, during which the components were concurrently moving. Since the patient table moved slower than the C-arm, "Patient – Assistant robot" pair achieved higher Spatial Agility and Mismatch Assignment Scores. All collisions were avoided, while human comfort was achieved in all tests.

Component-of-interest	Dynamic obstacle	Spatial Agility Score (%)	Mismatch Assignment Score (%)	Human Comfort Score
C-arm	Assistant robot	71	69	1
Patient	Assistant robot	75	85	1

Table 5-16: Performance scores of the system in Type 2 tests

Table 5-17 lists the performance indicators of the system in Type 3 tests, in response to varying update rates. The collision avoidance system failed to detect the conflict between components at the lowest update rate of the assistant robot. Higher update rates resulted with successful conflict detection and ensured human comfort. Spatial Agility and Mismatch Assignment Scores increased together with the update rate.

Update Rate	Spatial Agility Score (%)	Mismatch Assignment Score (%)	Human Comfort Score
1 Hz	-154	18	0
10 Hz	42	60	1
25 Hz	57	78	1
40 Hz	59	82	1
50 Hz	61	83	1
60 Hz	62	85	1
75 Hz	62	87	1
90 Hz	63	88	1
100 Hz	63	88	1

Table 5-17: Performance scores of the system in Type 3 tests

Table 5-18 lists the performance indicators of the system in Type 4 tests, in response to varying use-cases. “Assistant robot – Patient” pair achieved higher scores than the “C-arm – Assistant Robot” pair as the assistant robot moved slower than the C-arm during the tests.

Component-of-interest	Use-case of the assistant robot	Static obstacle	Spatial Agility Score (%)	Mismatch Assignment Score (%)	Human Comfort Score
Assistant robot	Needle attached	Patient	89	92	1
C-arm	Needle attached	Assistant robot	73	86	1
Assistant robot	Needle insertion	Patient	96	94	1
C-arm	Needle insertion	Assistant robot	60	90	1

Table 5-18: Performance scores of the system in Type 4 tests

Table 5-19 lists the performance indicators of the system in Type 5 tests, revealing the impact of the velocity-adaptive approach. The C-arm achieved higher Temporal Agility Score when the velocity adaptive mode was inactive, but its Spatial Agility Score was lower. In the velocity adaptive mode, the C-arm started its navigation at high-velocity and achieved the Spatial Agility Score of the slowest navigation.

Component-of-interest	**Velocity adaptive mode**	**Spatial Agility Score (%)**	**Temporal Agility Score (%)**
C-arm, low-velocity	Inactive	84	81
C-arm, high-velocity	Inactive	21	
C-arm, low-velocity	Active	84	58
C-arm, high-velocity	Active	84	

Table 5-19: Performance scores of the system in Type 5 tests

5.6 Interpretation of Results

In its core, the implemented collision avoidance system has accomplished avoiding all possible collisions within the given experimental setup and the digital replication parameters:

- All conflicts between the experimental pairs have been detected.
- The conflicts have been addressed on time.
- The system was aware of the context, i.e., it was able to identify the use-cases of the components and to distinguish between desired and undesired interactions.
- Particular actions, given in Table 2-3, were taken to resolve detected conflicts appropriately.
- No collision between components occurred. All mandatory and recommended functional requirements listed in Table 2-2 have been satisfied.

The utilized virtual representation, communication, and computation methods are proven to be competent in avoiding collisions in the diagnostic and therapeutic environments. The required data can be collected, represented, and processed in such a manner that the conflict detection and resolution can be handled in real-time, i.e., before the collision occurs. Lower Mismatch Assignment Scores reveal that the digital replication of the corresponding components was overcautious: Representation can be improved by bringing the assumptions closer to reality. This improves not only the Mismatch Assignment Score but also the Spatial Agility Score. On the contrary, components can get closer to each other, meaning that the human comfort can be violated, and the pair gets more prone to collisions.

Type 1 and Type 2 experiments demonstrated not only that the proposed system is capable of detecting and resolving the conflicts in the run-time, but also that it can handle concurrent movements of the components and does not require *a priori* path information. The provided virtual representation resulted in conflict detection and resolution distances, which were all in the range of human comfort: The detection did not take place at a distance between the conflicting bodies larger than the maximum allowed comfort distance nor smaller than the minimum allowed comfort distance. The representation parameters of the C-arm were assigned cautiously to ensure safety. Therefore, the Spatial Agility and Mismatch Assignment Scores associated with the C-arm are relatively small. Although human comfort has been satisfied in all interactions of the C-arm, there is room for improving its virtual representation.

Type 3 experiments yielded that collecting run-time data from the components at a higher rate increases the Spatial Agility, Mismatch Assignment, and Human Comfort Scores of the system at the cost of increased processing budget. Negative spatial agility score implies that the system is not agile with 1 Hz update rate; d_{det} is larger than the allowed maximum comfort distance between the bodies; the user cannot efficiently utilize the physical space. This specific test with 1 Hz update rate has been the only test case, which violated the human comfort: The conflict detection took place at a distance higher than the maximum allowed detection distance.

Type 4 experiments demonstrated that the proposed system is capable of distinguishing between the desired and undesired proximities. It can identify the desired interactions, assign proper separation distance between the relevant bodies, and allow these bodies to cooperate in the close neighborhood. As mentioned above, the digital twin of the C-arm has been achieved by assigning parameters cautiously to ensure safety, which resulted in relatively low Spatial Agility and Mismatch Assignment Scores. Nevertheless, all experiments yielded successful conflict detection and resolution distances within the human comfort zone.

Type 5 experiments demonstrated not only the impact of instantaneous velocity on the separation zone around a dynamic body; it further made the contribution of the velocity-adaptive approach on the agility of the system evident:

- When the velocity-adaptive mode is inactive, the spatial agility and the temporal agility are in competition. Higher instantaneous velocity causes the separation around the dynamic body to expand, the approach of the component-of-interest to an obstacle is restricted, hence the spatial agility decreases:
    - The low-speed motion of a component-of-interest from a certain point towards an obstacle results with higher spatial agility at the cost of longer travel duration.
    - When the component traverses the same trajectory at high-speed, the travel duration gets shorter at the cost of reduced spatial agility.
- On the contrary, when the velocity-adaptive mode is active, temporal agility of the system is improved without comprising spatial agility. Separation around the dynamic body expands regarding the high instantaneous velocity; when the body enters the observation zone, the instantaneous velocity is reduced, so the separation zone shrinks. With the active velocity-adaptive mode, higher Temporal Agility Score is achieved at the superior Spatial Agility Score.

The Temporal Agility Score has not been computed in Type 1, Type 2, Type 3, and Type 4 tests since the velocities of the components at the instants of conflict detection are not taken into account. Spatial Agility and Mismatch Assignment scores of the system could vary with respect to different instantaneous velocities.

The experiments further indicated that the quality requirements have been met:

- Preferring standardized data generation and communication methods provided the basis for inclusion of heterogeneous components in the computations. That means, independent components with different characteristics have been involved in the collision avoidance system. The system is not limited to specific components; any future component can additionally be introduced to the system.
- Within the given digital replication parameters, the proposed system accomplished avoiding the collisions by satisfying human comfort requirements. The conflicts have been detected and resolved within the human comfort zone ranges.
- In the context of the “C-arm – CRU” and “patient table – CRU” interface, an override mechanism has been implemented. This mechanism gives the

operator the possibility to drive the C-arm in a safety mode, i.e., with limited velocity, after the full-stop command, even if there is a continuous state of conflict detection. This mechanism allows the operator to have the ultimate control in the therapy suite and can be easily extended towards other electronically controlled components.

- Extensibility of the proposed approach has been demonstrated with the VTK-based mixed reality simulator. The data, which has been collected or generated with the collision avoidance system, has been served to and utilized by a third-party application for visualization purposes.

6

Discussions

The experiments have shown that the implemented solution is capable of addressing conflicts on time and avoiding catastrophic and critical collisions in the contemporary therapy suite. Agility has been improved by adapting the size of separation distances to instantaneous velocity and use-cases. The desired and undesired proximities of certain body pairs are discriminated, unnecessary interruption of movements is avoided. Human comfort is achieved by keeping minimal zones between components and preventing the movement interruptions when distance between components does not bring in safety threats. Nevertheless, the concept and methods of the collision avoidance system can be expanded and improved in future studies. This chapter details the points, which have been excluded in the study, and explains how a better system can be developed.

6.1 Collision models of components

Within the collision model, the C-arm has been represented as if the detector is fixed with respect to the C-arm. As it is connected to a prismatic and a revolute joint in reality, the detector has more degrees of freedom. The detector has been kept stationary with respect to the C-arm throughout the tests. The corresponding joints can be taken into account and directly integrated into the system for future expansions of the collision models so that the precision of component representation can be increased without requiring any change in the method.

The table-top is assumed to have 3 prismatic joints and a revolute joint. The utilized table-top for the evaluation has two more revolute joints for tilting and cradling, which have been neglected in the context of digital replication to mimic a basic interventional table and avoid complications in concept development. The virtual representation can easily be extended to include these joints, while no modification in the computations is needed to take this update in the action. Furthermore, some surgical tables have even more degrees of freedom, and they can be introduced into the system by using the methods which have already been used.

The patient is assumed to be stationary throughout the tests, which is not always the case in real-life. The patient can be additionally tracked and his/her transformation with respect to the table can be updated in the computations.

6.2 Run-time communication

Unexpected connection states may cause bring safety hazards in run-time and require further safety measures, such as:

- Although there are moving components, one or more components, e.g., the angiography system and the patient table, are not connected to the CRU; hence their instantaneous configurations are not reported to the system.
- The CRU receives a connection request from a component, whose identity is unknown to the database.
- A component disconnects from the CRU but continues its motions in the therapy suite.

The communication method can be improved so that it enables the connection of a brand-new component to the system in run-time. The new component reports the location of the component-profile file, to the CRU in the connection request. In addition, the virtual representation method could be expanded so that it immediately includes the new component in the digital twin and the separation computations.

6.3 The run-time representation of the components

Within the developed collision avoidance system, the movements of the C-arm during the rotational angiographic image acquisition are excluded. This is due to technical limitation, as the C-arm does not generate and report actual joint parameters during a rotational acquisition. On the other hand, the acquisition movements follow strict safety tests; therefore, the safety of the movement has been confirmed prior to the acquisition, and the operator is warned if any other component is entering the rotation trajectory. Instantaneous joint values of the C-arm can be quantified by means of additional techniques, such as optical tracking, and reported to the CRU to provide awareness to the collision avoidance system.

Transformation matrices of the components, i.e., the positions and orientations of their bases with respect to the global coordinate system, kept constant in run-time. The transformation matrix, reported to the CRU by the component in the connection request, is assumed to be constant in the run-time. Although this condition holds true for the angiography system and the patient table, it is not valid for all components such as assistant robot. During the experiments, the base of the assistant robot has been kept stationary. The DRU could allow the components to update their base transformations continuously.

6.4 Concept improvements

In image-guided therapies, pre-procedural medical images of the patient are used for procedure planning. These images and the planning landmarks are registered to the coordinate system of the angiography system and other imaging modalities, overlaid with the intra-procedural live images. Introducing the pre-procedural three-dimensional images as components to the collision avoidance system can result in improved procedural safety and decreased risk of complications. These non-physical components can be mapped to physical components in the patient body. Thereby undesired interactions between the surgical or interventional devices and the organs can be avoided, such as damaging a vessel by a needle.

Quantifying the configuration of non-robotic components in run-time by external means, for instance optical tracking, requires further improvement. A single optical tracking camera has been used for introducing the concept and carrying out the experiments. However, a single camera is not sufficient to ensure continuous data collection due to the frequent loss-of-sight problems. Continuous tracking could be ensured in a real-clinical setup by using multiple cameras or enabling other tracking modalities.

Human beings are represented to have a unique stiff body with 4 degrees-of-freedom, movements of their extremities are ignored in the context of this study. The existing representation could be fine-tuned by defining further joints for representing the extremities so that the precision of human representations could be improved. Corresponding quantification methods, such as optical tracking system, could be implemented to digitize the values of these additional joints in run-time. Furthermore, various human models could be employed to represent different sizes of human beings.

Mismatch Assignment Scores between a specific component pair could be used online to improve the assumptions on constant virtual representation parameters in run-time, namely the latency, associated uncertainty, and braking distances. This allows continuous monitoring of the assumptions and their dynamic update. Therefore, the overall performance of the system could be improved. Machine learning algorithms could be employed to determine individual impact of the agility parameters to fine-tune assumptions in run-time, and to make these parameters time varying.

7

Conclusion

Advancements in medicine and technology alter the conventional treatment methods and requirements. Together with the rise of image-guided as well as the robot-assisted therapies, surgical and interventional practices evolve. This practical evolution is accompanied by introduction of therapeutic devices into the modern operating room and interventional suite. Hybrid operating room is a combination of operating room and interventional suite: Surgical and interventional devices are found in the same environment, leading to the utilization of the infrastructure by multiple disciplines for a wider range of purposes. The contemporary therapy suite in this work refers to today's operating rooms, interventional suites, and hybrid operating rooms together, which are equipped with modern therapeutic devices.

The therapy suite is a highly crowded and dynamic environment. It is occupied not only by devices but also by a multi-disciplinary team of people. These devices and people are in continuous mobility throughout the procedure. As the entire procedure is patient-centric, the devices, people, and their movements are concentrated around a single spot, which is the patient. The devices are mostly stand-alone and uncooperative, unaware of each other and their surroundings. All components are manipulated and displaced by a human operator. The lack of awareness between the devices as well as human mistakes during the operation of these devices lead to collisions. Collision in a therapy suite can lead to severe damage not only on therapeutic devices but also the staff members and patient. The crowded and dynamic nature of the therapy suite brings in safety threats.

The existing collision avoidance solutions in the therapy suite are limited to certain devices. These specific solutions prevent the collisions between the dedicated devices, but they cannot avoid the collisions with other prominent devices in the same environment. Furthermore, a comprehensive collision avoidance system, which aims at avoiding collisions between any devices and people in the therapy suite is not reported in the literature. This work aims to conceptualize and implement a comprehensive collision avoidance system for the contemporary therapy suite.

Development of a collision avoidance solution for therapy suite only follows clear understanding on the physical and dynamic characteristics of the environment. Devices and human beings have been thoroughly analyzed, their movements and interactions with each other are observed during the surgeries and interventions. The devices and their interactions are categorized based on the impact and severity of collisions. Generic components have been defined, catastrophic and critical collisions are identified. The findings have been validated by two interventional radiologists and a surgeon. Functional and quality requirements are derived from these findings. At its core, the system shall ensure safety in the suite without disturbing agility of the procedure. Utilization of the system shall be acceptable by the staff members; it shall not violate human comfort. Categorization of components, interactions, and collisions as well as the derivation of requirements have been a major contribution of the work.

The work conceptualizes a solution, based on adaptive separation of components. It assigns a safety zone around the bodies of components, which is a function of the instantaneous velocity of the moving body, use-case, and update rate of the component. This adaptive separation assignment shall ensure safety in the therapy suite, improve agility of the processes, and comply with the human comfort requirements.

The solution is implemented based on the real-time swept volume and distance computation method by Täubig, Bäuml, and Frese. This method is introduced for avoiding the self-collisions of a humanoid robot, which is extended in the scope of this work to meet the therapy suite requirements. The complete solution for generating a digital twin of the therapy suite, representing the components properly, facilitating communication between the components and the collision avoidance system, distinguishing the safety threats from desired proximities, and resolving the safety threats is original contribution of the work. The solution is comprehensive and extensible: It aims at avoiding collisions between any components in the environment, it can be applied to future components without modifying the methods.

Due to the lack of a methodology in the literature to assess the performance of the implemented system, performance evaluation criteria are described as part of the work. The implemented solution is tested in an experimental intervention room and its performance is evaluated. The experiments have shown that the solution is capable of addressing potential collisions on time and avoiding catastrophic and critical collisions in the contemporary therapy suite. Agility has been improved by adaptive separation assignments. The desired and undesired proximities of components are discriminated, unnecessary interruption of movements is avoided, and human comfort is achieved.

The conceptualized and implemented collision avoidance system ensures the safety of the components and agility of the performance in the contemporary therapy suite.

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