Electromagnetic Simulation of Robotic Dynamic Scenes for Novel Sensor Developments

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Abstract. To ensure the safety and efficiency of human-robot collaboration, new sensor modalities are required that capture a robot's entire environment and provide a sense of touch. Robotic skins based on either pressure or capacitive sensors provide a sensing range of up to 20 cm and enable the robot to react to contact with its environment. A novel robotic skin with a sensor that utilizes the electromagnetic (EM) properties of flexible metasurfaces could have a sensing range of up to 1 m and enable predictive motion planning and safe robot control. The development of this sensor requires EM simulation of dynamic scenes, which cannot be performed directly with existing simulators. To overcome this challenge, we propose and implement a software bridge between a robotic and a full-wave EM simulator to facilitate the development of novel sensors. We experimentally validated our framework by simulating two dynamic scenes and determining the scattering parameters of skin-mounted antennas that correlate with the distance between the object and the sensor.

1 Introduction

The rapid advancement of robotics has led to an increased presence of robots in both human-centric and industrial environments, giving rise to new challenges related to system efficiency and human safety. To effectively interact with humans, robots require accurate real-time perception of their environment to minimize the risk of collision. Commonly used sensors (e.g., cameras and lidars) offer rich semantic information, but may fall short in completely capturing the surrounding environment due to a restricted field of view or occlusions, and they often operate at a limited frame rate. Consequently, tasks performed by robots are often too slow and too simple, posing an important obstacle to robot utilization in healthcare, agile manufacturing and many other fields. To address these challenges, one potential solution involves equipping robots with novel sensor modalities, such as a flexible sensing skin [1], in addition to standard perception sensors. This integration would enhance the overall perception capabilities of robots, mitigating risks and enabling their effective deployment in diverse fields.

Existing stretchable e-skins of pressure sensors [2][3] are based on piezoelectric, piezo-resistive, conductive and capacitive sensing, and some companies (e.g.,

Fogale Robotics, Bosch) offer commercial solutions [4]. Yet, pressure-based proximity skins require contact, while capacitive sensors have a sensing range of only up to 20 cm and suffer from low measurement accuracy in the nonlinear detection range. A new sensor modality could exploit the electromagnetic properties of flexible metasurfaces [5][6] for near-field and far-field sensing based on surface waves and their possible transformation into leaky waves. The measurement of the correlation between transmitted and received signals at all pairs of ports on the skin can be used to monitor the effects of folding the flexible skin and provide measurements of position of objects in the surrounding environment. This topic is an active area of research and is investigated in the scope of the EU Pathfinder Open project *Flexible intelligent near-field sensing skins - FITNESS*[1].

To develop this sensor and enable its utilization in collaborative robotics, first we need to be able to estimate positions of ports mounted on the skin for each robot configuration. Next, we need to simulate the possibly dynamic EM environment and analyze the obtained scattering parameters (S-parameters) to infer the positions of objects in the environment. This process requires both robotic and full-wave EM simulators. Widely available robotic simulators [7][8] do not consider object EM properties (e.g., permittivity and permeability) and are not able to simulate EM phenomena. On the other hand, full-wave EM simulators only simulate static scenes and lack the ability to manipulate kinematic chains.

To address these issues, in this paper we propose a simulation framework that features a software bridge between a robotic and a full-wave EM simulator, enabling the EM simulation of dynamic scenes. Our framework relies on a robotics simulator for creating dynamic scenes and reasoning about robot kinematics, while full-wave EM simulator computes the desired S-parameters. The proposed software bridge discretizes the robotic dynamic scene and automatically conducts the EM simulation of the scene at each time instant. We experimentally validated our framework by simulating two dynamic scenes and determining the S-parameters of skin-mounted antennas that correlate with the distance between the object and the sensor. In addition to the novel e-skin development, the proposed simulation framework could be used to develop other novel sensors that are based on the EM phenomena.

2 The proposed simulation framework

Consider a robot arm equipped with a smart skin that has a set of antennas. We want to simulate the S-parameter values for these antennas in order to infer the distance of objects from the skin and, if possible, their position relative to the robot. We want to know the S-parameter values at each point during the robot arm motion. To this end, we propose a simulation framework that leverages existing robotic and full-wave EM simulators. The robotics simulator takes the robot configuration at each discrete time instant of the robot's trajectory and, given the robot model, computes forward kinematics. The proposed software

[1] https://fitness-pathfinder.eu

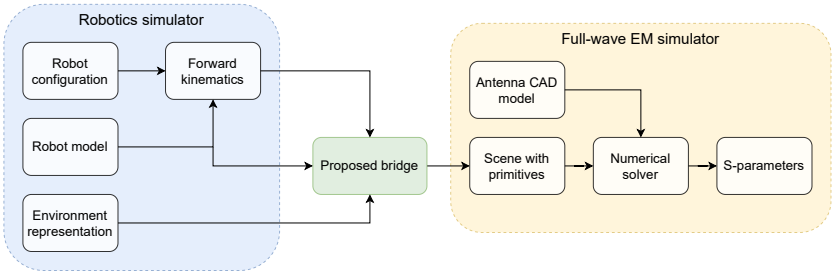


Fig. 1: The architecture of the proposed simulation framework.

bridge uses geometric primitives (e.g., spheres and cubes) to approximate the environment representation and the robot model at the calculated pose. This scene is passed to the full-wave EM simulator which uses a numerical solver and the antenna CAD model to compute the S-parameters. The architecture of the proposed simulation framework is shown in Fig. 1.

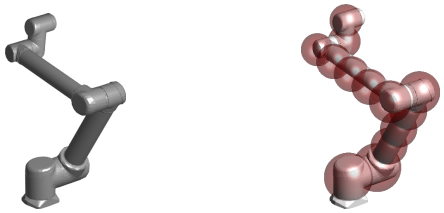
2.1 Robot and environment modeling

The robot configuration at a given time instant t_i is defined as a set of joint positions $\mathbf{q}_i$ in the configuration space $\mathbf{q}_i \in \mathcal{Q} \subset \mathbb{R}^n$ which comprises all feasible joint positions, where n is the number of degrees of freedom (DoF). Similarly, the robot's end-effector poses $\mathbf{x}$ form the task space $\mathbf{x} \in \mathcal{X} \subset \mathbb{R}^p$. The robot's forward kinematics function is defined as the following nonlinear mapping

$$\mathbf{f} : \mathcal{Q} \rightarrow \mathcal{X}. \tag{1}$$

The robot's body can be modeled as a set of arbitrary number of points, $\mathcal{B} \in \mathbb{R}^w, w \in \mathbb{N}$. Given a robot's configuration $\mathbf{q}_i$, the forward kinematics function can also provide the pose of a point $b \in \mathcal{B}$ of the robot body in Euclidean space.

In practical applications, the set of points $\mathcal{B}$ can be approximated with a set of geometric primitives (e.g., spheres, polyhedra, ellipsoids) that encompass the robot's body. In the proposed simulation framework, we deem the robot body as a set of spheres, which is a representation ubiquitously utilized in trajectory optimization methods [9]. In the case of a robotic arm, we manually generate a discrete set of spheres for each link. This is illustrated in Fig. 2, where for the Universal Robots UR10 arm we show the mesh model that closely resembles the actual robot, both with and without the corresponding set of spheres overlayed. By using spheres as geometric primitives, the nearest distance from an obstacle to any point in the set $\mathcal{B}$ is simple to compute, which enables efficient collision checking that is crucial for achieving real-time algorithm execution on current hardware. While the set-of-spheres robot representation is not the most accurate way of modeling the robot's body, its simplicity facilitates the EM simulation of the robot arm in a dynamic environment. We choose this representation since EM simulation with a mesh model can become computationally complex, requiring



(a) (b)

Fig. 2: An example of representing the Universal Robots UR10 robot with a mesh model (a) and with a set of spheres (b). The robot can be adequately represented by only 13 spheres, which allows particularly efficient collision checking.

days to simulate a complex dynamic scene. The mentioned simplicity also implies that a set-of-spheres model can easily be manually constructed by a human operator, enabling fast deployment in practical applications.

2.2 S-parameters

The S-parameters describe how the electrical signal of a single frequency is scattered or transmitted within the network and compress very complicated networks into black-box models [10–13]. They are often used in radiofrequency (RF) and microwave engineering to characterize behavior of linear electrical networks (e.g., an RF amplifier or an antenna), both in free space or in the presence of some objects. The S-parameters provide the relation between power waves traveling in and out of the network, which is a more convenient representation at higher frequencies in comparison to voltage and current [14]. The waves traveling into the n-th port of the network are called incident waves and denoted with a_n, while the waves traveling out of the network are called reflected waves and denoted with b_n. Incident and reflected waves for a 2-port network are shown in Fig. **??**.

The expression which relates the voltage U_n and current I_n at port n with the incident and reflected wave is

$$a_n = \frac{U_n + I_n Z_0}{2\sqrt{\mathrm{Re}(Z_0)}}, \quad b_n = \frac{U_n - I_n Z_0^*}{2\sqrt{\mathrm{Re}(Z_0)}}, \tag{2}$$

where Z_0 is an arbitrary reference impedance that may be represented with a complex number, but typically it is set to the characteristic impedance of the transmission lines in the system (e.g., $Z_0 = 50\,\Omega$). As noted before, the S-matrix gives the relation between all a_n and b_n, $n = 1, 2, ..., N$ for the N-port network

$$\mathbf{b} = \mathbf{S}\mathbf{a}, \tag{3}$$

where $\mathbf{a}$ and $\mathbf{b}$ are $(n \times 1)$ vectors, while $\mathbf{S}$ is an $(n \times n)$ matrix with elements (S_{ij}). From this equation then follows

$$S_{ij} = \left.\frac{b_i}{a_j}\right|_{a_n=0, \forall n \neq j}. \tag{4}$$

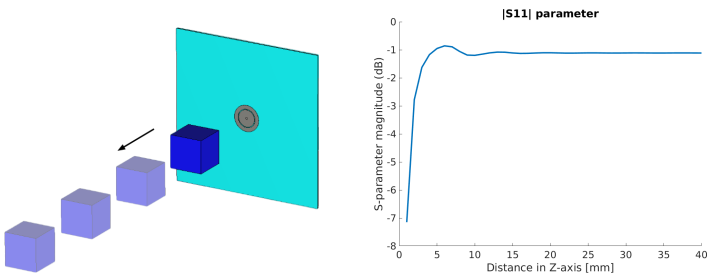
The parameter S_{ij} can be interpreted as the ratio of a power wave leaving at port i, when there is only an incident power wave at port j. In case of $i = j$, the S_{ii} is the reflected power at the same port. For this reason the diagonal elements of $\mathbf{S}$ are called reflection coefficients, while the off-diagonal elements are called transmission coefficients. In general, S_{ij} is a complex number because the network affects both the magnitude and the phase. The S-parameters of a multi-port network mounted on the robotic skin are dependent on the electromagnetic properties of the environment, which could be leveraged to develop a new sensor that can accurately determine positions of objects relative to the skin.

2.3 Bridging robotics and full-wave EM simulation

In order to conduct the full-wave EM simulation of robotic dynamic scene, we rely on the robotics simulator to create a scene with the robot and environment model. Our robotics simulator of choice is Matlab Robotics Toolbox, which has many existing robot models and can be interfaced with the Robot Operating System (ROS) for communication with the real-world robot. For the full-wave EM simulation, we use the industry-standard CST Studio Suite software. The proposed software bridge enables communication between the two simulators by creating a local object linking and embedding (OLE) automation server using an OLE-compliant component object model (COM) server. COM is an object-oriented system designed for creating binary software components, allowing them to interact with a variety of programming languages. We compile our bridge in the Microsoft Windows system as the Matlab COM function is exclusively compatible with this platform. Using our bridge, we can create or load the simulated robotic dynamic environment in Matlab and pass the information to the CST simulator. Our implementation approximates the scene from a robotic simulator with geometric primitives and passes the scene description at each discrete time instant to the full-wave EM simulator, which then uses a numerical solver and the antenna CAD model to compute the ground-truth S-parameters. The results of the EM simulation, in our case the obtained S-parameters, are passed back for analysis and visualization.

3 Results

To evaluate the proposed simulation framework, we conducted two dynamic scene scenarios. The first scenario featured a single static antenna and a box object moving away from the port. We calculated the S-parameter of the antenna port through time and graphed its value against the increasing distance. In the second scenario, a Kuka Iiwa 14 robot was equipped with two antennas, resembling a simple e-skin. The robot executed a trajectory in close proximity to the large box obstacle resembling a wall in the environment. We computed the S-parameters of both antenna ports, which could subsequently be used to infer the distance of nearby objects. Both experiments were performed on a system with a 3.5-GHz Intel Core i7-7567U processor and 16 GB of RAM.



(a) Moving box scenario (b) S-parameter magnitude

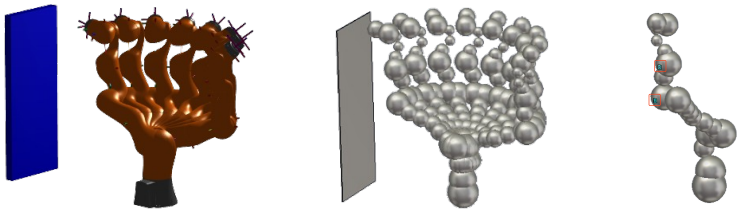
Fig. 3: The experimental scenario featuring (a) EM simulation of a box moving along the z-axis of the sensor antenna and (b) the corresponding S-parameter depending on the distance between the moving box and the antenna.

3.1 Moving box scenario

We conducted the first simulation in CST with a 26 GHz wave launcher object with 4.64x4.64 cm dimensions and a perfect electric conductor (PEC) box object with dimensions 0.5x0.5 cm. We used the proposed software bridge to control the movement of the PEC box in the CST simulator through Matlab. The distance in the z-axis between the launcher and the box was discretized at 1 mm intervals, resulting in 40 consecutive simulations, effectively simulating a dynamic environment, as illustrated in Fig. 3a. Given a discretization time of 0.1 s, the box moves with a translational velocity in the z-axis of 0.01 m/s. The simulation was executed using hexahedral mesh and the TD-C calculation type. Each simulation took approximately 10 minutes of computation time. The obtained S_{11} parameter magnitude increases with the distance along the z-axis of the port, as shown in Fig. 3b, a result that may be used to determine the distance of a moving object relative to the port, facilitating new sensor developments. The distance at which we observe changes in the S-parameter can be increased with different object size and with a different antenna type. We leave this analysis for future work.

3.2 Robotic arm trajectory scenario

For the second scenario, we used Matlab to simulate a robot arm trajectory execution near a wall in the environment. We used the proposed software bridge to discretize the robot trajectory with duration of 1 s, compute the forward kinematics at every time instant, and represent the scene using PEC box and spheres in the CST simulator. The visual representation of the environment through time in both Matlab and CST is shown in Fig. 4. Additionally, using our bridge we imported a preexisting discrete copper antenna model into CST and placed two instances of the antenna on different joints of the robot, as shown in Fig 4c. The dimensions of antennas are 1.8x2.2 cm, and they operate at 10 GHz. We



(a) Matlab scene (b) CST scene (c) Arm spheres

Fig. 4: Experimental scenario including Kuka Iiwa 14 and PEC wall in (a) robotics simulator, (b) EM simulator. The arm is approximated with a set of spheres and has two equipped antennas, visible inside red squares (c).

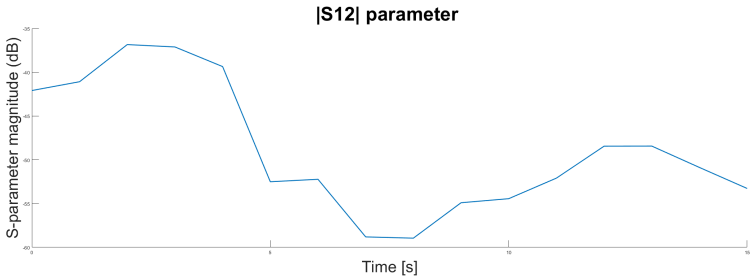


Fig. 5: S_{12} parameter magnitude in the robotic arm trajectory scenario.

manually adjusted the cells-per-wavelength mesh parameter to optimize simulation runtime. Each simulation took approximately 90 minutes of computation time. While the obtained S-parameters magnitudes, which are shown in Fig. 5, cannot be directly correlated to distance, the proposed simulation framework can be utilized to verify analytical models or to collect large amounts of data for training deep models. In particular, the S_{12} parameter can be used to determine the relative position of sensors on the flexible skin.

4 Conclusion

In this paper, we presented a framework that enables the EM simulation of robotic dynamic scenes. We proposed a software bridge that first takes robot and environment representations from the robotic simulator and approximates the scene with geometric primitives. The scene information is then passed to the EM simulator in order to compute the S-parameters at the ports, enabling the development of sensors based on EM phenomena, e.g., a novel robotic skin. We experimentally validated our framework by simulating two dynamic scenes and determining the S-parameters of skin-mounted antennas that correlate with the distance between the object and the sensor. We believe that our framework can

be leveraged for modeling novel sensors that are accurate and efficient, serving as a first step for evaluation and comparison with analytical models. In future work, we will analyze how different object and antenna properties affect the S-parameters. We will also investigate precision and repeatability in real-world conditions, a well as the effect of interferences.

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