MOGI: Multi-Orientation Gesture Interaction with a 140GHz High-Resolution On-Chip Radar

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Abstract End-users are today used to interacting with interaction surfaces of various orientations, either graphically with a mouse or pointer, or tactilely with a finger. They are also increasingly used to interacting gesturally with surfaces in multiple orientations, ranging from horizontal and oblique surfaces to vertical surfaces, most often using mid-air gestures. They now want to get used to interacting in the same way with any interface surface involving a radar, which has the advantage of being insensitive to conditions of lighting, visibility, and privacy. This paper motivates radar gesture interaction in front of interactive surfaces with multiple orientations and aims to compare the accuracy of gesture recognition in different orientations based on three categories of gesture candidates: lateral, horizontal, and vertical.

Key words: Gesture input, Gesture recognition, Multi-context interaction, Multi-orientation gesture interaction, Multi-surface interaction, Radar-based gestures

1.1 Introduction

Gesture interaction, since it has been supported by efficient algorithms, ranging from 2D [18, 7, 23, 31] to 3D [6, 4, 5, 12, 36] and empowered by precise devices or sensors, such as radars [35], stands at the forefront of today's human-computer interaction (HCI) applied in many domains of human activity [8]. In particular, harnessing the

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capabilities of radar-based systems [14] deployed in various configurations offers new opportunities for understanding and interpreting human gestures [26], mainly hand gestures [12, 13] and arm gestures [17].

Gesture recognition based on radar in multiple orientations relies on sophisticated radar systems capable of capturing and analyzing gestures from different angles and perspectives, in particular with multiple input-multiple output (MIMO) capabilities [10, 1]. Unlike traditional approaches that may be limited by line-of-sight constraints or environmental factors, radar systems offer unparalleled flexibility and robustness. By deploying radar sensors strategically in various orientations, it becomes possible to capture a comprehensive view of human gestures in three-dimensional space. On the one hand, there is an increasing demand for recognizing gestures by a radar, whether they are classical [34] or specific to radars [33]. On the other hand, many techniques, borrowed from signal processing, machine learning, and more recently deep learning (see a systematic literature review in [28], play a pivotal role in synthesizing or fusing data from multiple radar sources or multiple antennas of the same radar, enabling accurate, real-time recognition of gestures. Anyway, radar-based interaction is subject to several challenges, such as:

1. **Multi-path interference:** Radar signals may reflect on surfaces and objects present in the users' environment, leading to multi-path interference and distortions, thus resulting in inaccurate gesture detection.
   Solution: Advanced signal processing techniques [26], such as beamforming and adaptive filtering, can mitigate multi-path interference by isolating the desired signal from reflections. Additionally, using multiple radar sensors in different orientations can help triangulate the position of the gesture and improve accuracy.
2. **Ambiguity in gesture isolation and interpretation:** Radar signals may capture multiple gestures simultaneously or misinterpret unintended movements as gestures, leading to ambiguity in gesture recognition. The starting and ending points of the gesture should be isolated.
   Solution: Machine learning can enhance accuracy by learning patterns and distinguishing between intentional gestures and background movements. Training the system with a diverse dataset of gestures in various orientations should improve its robustness and ability to generalize.
3. **Environmental disturbances:** External factors such as electromagnetic interference, weather conditions (*e.g.,* a difference of temperature or of hygrometry), and physical obstructions can degrade radar signal quality and impact gesture detection reliability.
   Solution: Radars with adaptive modulation schemes and frequency agility can help mitigate the effects of environmental disturbances. Additionally, integrating complementary sensor modalities, such as cameras or infrared sensors, can provide redundancy and enhance overall system reliability. For example, a Leap Motion Controller can complement a radar [5]. While radars can penetrate several materials [21, 29], there is still some material sensitivity that needs to be considered [13].

4. **Calibration and synchronization:** Aligning and synchronizing multiple radar sensors operating in different orientations can be challenging [17], leading to inconsistencies in gesture detection and tracking.
   Solution: Implementing robust calibration and synchronization protocols ensures that data from multiple radar sensors are accurately aligned in time and space. This can involve using reference points or landmarks to calibrate sensor positions and employing time synchronization. There is also an ongoing effort to reduce the number of synchronizations needed to operate the same radar in multiple configurations to avoid re-calibrating the same radar or another one.
5. **Power consumption and cost:** Deploying multiple radar sensors in different orientations may increase power consumption and system costs, particularly in battery-operated or cost-sensitive applications.
   Solution: Radar design, particularly in its physical layout of antennas, should be further investigated for low power consumption and explore integration with low-power microcontrollers or system-on-chip solutions [6]. Additionally, leveraging advances in radar technology, such as integrated circuit miniaturization and cost-effective manufacturing processes, should mitigate cost concerns.
6. **Privacy and Security:** Since a radar can be integrated into a variety of objects or materials, it becomes invisible to the users [21], which on the one hand frees them from a feeling of surveillance and engages them in a sense of confidentiality, but on the other hand can still inadvertently record sensitive information or be susceptible to unauthorized access, raising concerns about privacy and security.
   Solution: Authentication mechanisms can secure communication between the radar, the computer that processes its signal, and the actuator. Privacy regulations should adopt privacy-by-design principles to minimize data collection and anonymize user information wherever possible.

Despite these challenges, radar-based gesture interaction has sparked significant interest across various domains for its potential to revolutionize the way we can interact with computer-based systems and actuators in ambient environments. In the context of multi-platform [3] or multi-context systems [11], this paper aims to explore the extent to which candidate gestures can be accurately and robustly recognized by one or more radars located in interaction surfaces with multiple orientations, whether lateral, horizontal or vertical. To this end, section 1.2 reviews the literature in terms of multiple orientations from both a general interaction and a radar-specific point of view. Section 1.3 then presents the high-frequency radar capable of capturing gestures in fine detail that we will consider in multi-orientation gesture interaction () in section 1.4. Section 1.5 proposes three categories of gestures that are admissible for different orientations to be investigated. Section 1.6 concludes this paper and presents some future avenues to this work.

1.2 Related Work

This section progressively reviews some work related to multi-orientation interaction, first with the graphical modality, then with the gestural modality, first with any other sensor than a radar, and then with a radar.

1.2.1 Multi-Orientation Graphical Interaction

Lachenal and Coutaz [16] defined an ontology of interaction surfaces, a central concept in our work since everything can be considered as an interaction surface as soon as a radar is embedded in it. Now that our ambient environment is equipped with electronic chips and interconnected sensors, it offers an array of opportunities for new forms of interaction. In this environment, interaction surfaces play a crucial role.

In civil architecture, surfaces break down our ambient environment into zones, such as the rooms in a house or the waiting areas in an airport, enabling activities specific to each zone to emerge or be carried out via each surface. In HCI, the screen remains the preferred interaction surface, but is increasingly replaced by other surfaces. Each of these surfaces has a specific purpose and interactional qualities: one is movable while the other is fixed, one is rigid while the other is deformable. All these surfaces are widespread and have special relationships with us, particularly interactional relationships: all surfaces are perceived by the senses, manipulated by our motor actions and serve a purpose.

There are two types of interaction surface [16]: (1) an *action surface* is a subset of a physical surface on which a user can act directly with effectors or indirectly via sensors; (2) an *observation surface* is a subset of a physical surface that an actor can observe using sensors.

The topology of interaction surfaces is fundamental as it expresses how different surfaces are organized in space to support a distributed interaction. Lachenal and Coutaz [16] defined *surface coupling* and *compatibility* between surfaces. The topology defines the position and orientation of entities in a reference system, including actors, surfaces, and instruments. If we focus on interaction surfaces, the state of the art shows that the spatial relationships between surfaces are important. For example in BUILD-IT [24], the graphical representations of domain concepts depends on the **orientation** of the interaction surface: the same concept is represented in 3D on a vertical surface (a wallscreen and a laptop) and in 2D on a horizontal surface (a tabletop). The detection of a change in the orientation of a surface, or its displacement in space, brings into play localization algorithms that have yet to be mastered. The physical characteristics of an interaction surface include, but are not limited to[16]:

- The geometric shape: a 2D surface such as a regular plane, a regular or irregular polygon, or a 3D surface, such as induced by a spherical display.
- The size: the extent of the shape.

- The weight: the mass of the surface.
- The material: the constituent materials of the surface, such as wood, glass, and PVC [29], fabrics [21], plaster, plastic, water, or steam.
- The texture: uniform or irregular.
- The social use: public, private, semi-private.
- The proxemics use: close intimate (0-15 cm), intimidate (15-45 cm), personal (45 cm-1.2 m), social (1.2 m - 3.6 m), public (¿3.6 m), and remote.

1.2.2 Multi-Orientation Interaction by Gesture

Research on tactile interaction on surfaces has shown that performance and error rates are impacted by the orientation, with tapping being faster on vertical surfaces (by at least 5%) and dragging being faster and more accurate on horizontal surfaces [23]. Furthermore, the orientation of objects on horizontal displays can be used to establish personal space, create a public space, and as part of gestures. Marquardt [18] suggests that a continuum of interaction space, where gestures and direct touch are integrated, can lead to more expressive interactions. Xia et al. [35] explore the use of surface and motion gestures on mobile devices for 3D manipulation of objects on large surfaces, finding reasonably good agreement between gestures and input.

Regal [25] also identified gesture preferences for a vertical or horizontally-oriented multi-touch input device were tested. Kruger [15] shows that adjusting the orientation of objects can be used to establish personal space, to create a public space, and is used as a significant part of gestures that direct comments, ask for help, and indicate interest. For example, the Hands-Up system [20] takes advantage of the ceiling as a horizontal interaction surface to display information and to enable an end-user laying on a bed to interact using a Microsoft Kinect. For example, opening and closing the hand near the head turns the lights on and off, respectively. Performing a lasso gesture with two fingers near the head and making a circular movement horizontally will toggle all items displayed on/off.

1.2.3 Multi-Orientation Interaction by Radar-based Gestures

Radar-based gesture recognition has seen significant advancements in recent years, with neural network-based models for gesture classification and orientation estimation, achieving high accuracy rates. Doppler radars have been extensively tested [6, 36], including Huang [13] who introduced a Doppler radar with metamaterial-based antennas for hand-gesture sensing

Latern [37] presents a novel system for dynamic continuous hand gesture recognition based on a frequency-modulated continuous wave radar sensor and employs a recurrent 3-D convolutional neural network to classify dynamic hand gestures. Martinez and Villarreal [19] introduced the concept of zenithal gestures: when people

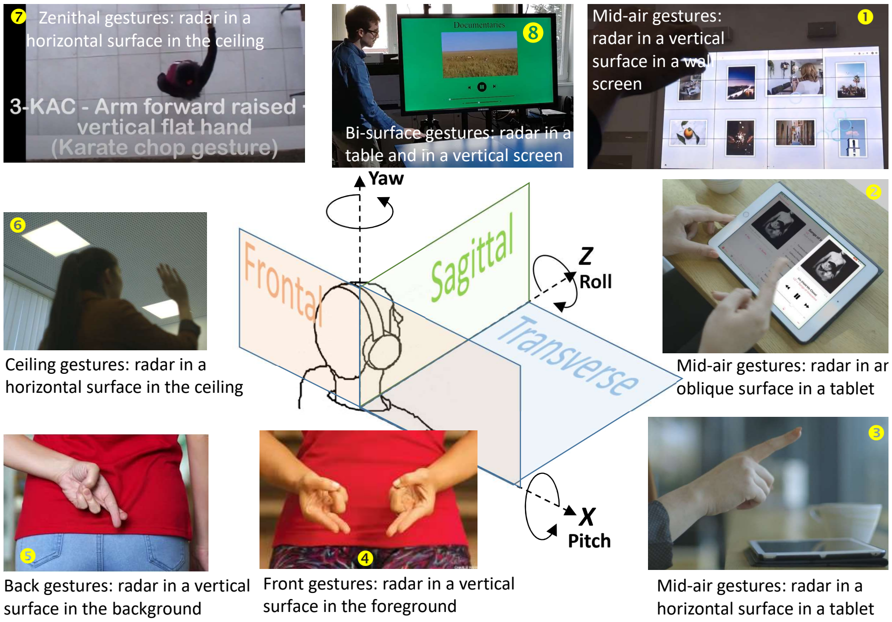

Fig. 1.1: Radar-based interaction with surfaces having different orientations: (1) mid-air gestures in front of a vertical wall-screen[22]; (2) mid-air gestures in front of an obliquely-oriented tablet (Source: IMEC video); (3) mid-air gestures on top of a horizontal tablet (Source: IMEC video); (4) front gestures with a radar in the foreground (Source: Hand gestures); (5) back gestures with a radar in the background; (6) ceiling gestures with a radar in the ceiling (Source: IMEC video); (7) zenithal gestures from the ceiling [19]; (8) bi-surface gestures with two surfaces (Source: RadarSense video).

are entering a building, they can interact with the ambient environment by performing arm gestures that are captured by a sensor placed in the ceiling, at the zenithal position of their standing, hence its name. Fig. 1.1 shows representative examples of radar-based interaction with surface having different orientations.

1.3 IMEC’s 140 GHz Radar

While low- or mid-frequency radars can be used for mid-air gesture interaction [28], high-frequency radar offers the ideal trade-off regarding performance, cost, energy usage, and dimensions. Radar systems with carrier waves exceeding 100 GHz are, in principle, able to detect subtle gestures thanks to enhanced depth resolution, to measure the gesture speed accurately thanks to Doppler shifts (which is very important for motion gestures), and can be very compact, especially when antennas

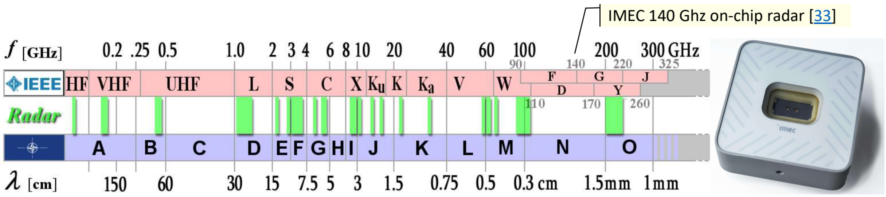
IMEC 140 Ghz on-chip radar [33]

Fig. 1.2: IMEC’s 140 GHZ radar positioned on the IEEE Continuum.

are integrated on the radar chip. For these reasons, we chose the 140GHz high-resolution on-chip radar (Fig. 1.2) developed by the Interuniversity Microelectronics Centre (IMEC) [1]. The two main components of this radar chip are a transceiver with integrated antennas and a low-power phase-locked loop (ADPLL) to generate the modulated carrier wave. These two components are designed in 28nm bulk CMOS technology, enabling high integration and low-cost volume production. This radar holds in a $10 \times 10mm^2$ package, thereby making it very compact while achieving superior radar performance: a +11.5 dBm effective isotropic radiated power (EIRP) per TX element, a 10 GHz bandwidth, a $> 55mm$ range resolution and sub-mm range accuracy, and a wideband transition to and from the antenna.

1.4 Multi-Orientation Gesture Interaction with the 140 GHz Radar

Based on the ontology of interaction surfaces [16], we define *Multi-orientation Gesture Interaction* (MOGI) with a radar as the capability of an ambient environment to capture the end user’s gestures in a single view from interaction surfaces having multiple possible orientations, such as horizontal, vertical, and oblique. These orientations can be materialized through different surfaces that are tracked along the three traditional dimensions (Fig. 1.3): frontal, lateral, and transversal.

1.5 Candidates for Multi-Orientation Gesture Interaction

The accuracy of radar-based gesture recognition depends mainly on the surface area of the gesture exposed to the radar, its distance, and its movement over time [28]. Two gestures with a very close exposure surface, for example two fingers or three raised fingers, are likely to be confused for this reason. It is therefore essential to examine candidate gestures for multi-orientation recognition as a function of the surface area exposed in the direction of the radar.

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[1] See `https://www.imec-int.com/en/expertise/radar-sensing-systems/140ghz-radar-modules`

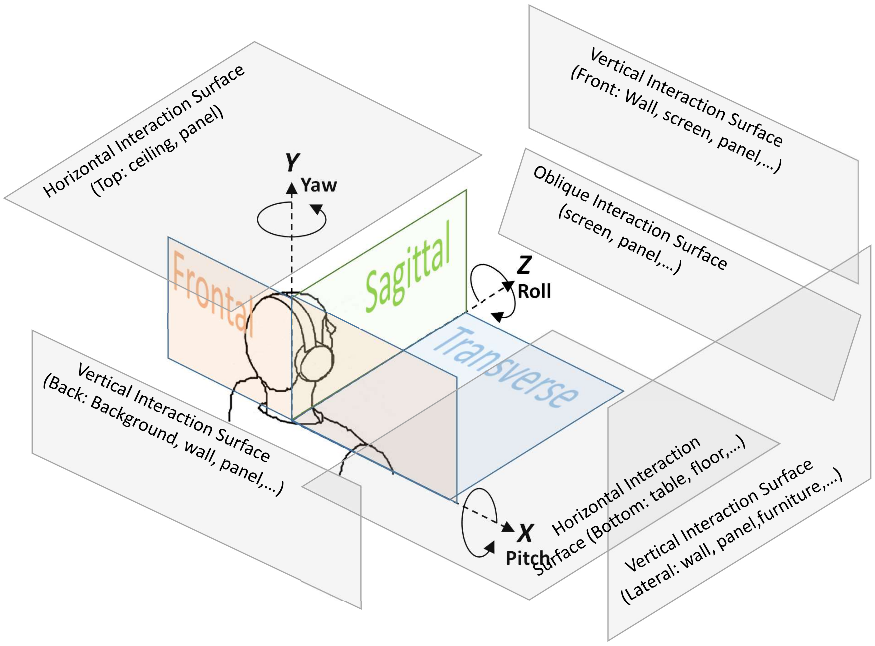

Fig. 1.3: Interaction surfaces with different orientations in different planes.

Candidates for a **lateral** radar-based gesture interaction include:

1. *Pointing gestures*: deictic gestures, which point towards specific directions to select objects or to indicate directions, are welcome as soon as the outstretched arm provides sufficient, differentiating lateral exposure.
2. *Tap gestures*: tapping or lightly hitting the air to trigger, to confirm actions, or to select items in a menu [18] are admissible candidates provided that their lateral exposure is significant enough.
3. *Swiping gestures*: side-to-side swipes, which are often used for navigating through menus or flipping through pages [23], are admissible provided that their lateral exposure, which varies over time as a function of the swipe, is differentiating.
4. *Flicking gestures*: flicks, which are considered as swiping gestures that are quickly performed over a small length, are often used for scrolling through content or dismissing items.
5. *Hand wave gestures*: waving a hand from side to side or making specific patterns with a hand, which are often used for activating or dismissing notifications or controlling media playback, can be detected by lateral radars [12].
6. *Zooming gestures*: pinching or expanding gestures made with the hands, not the fingers, can be used for zooming in or out on content [22], similar to pinch-to-zoom on touchscreens, except that the fingers are too small to be detected.
7. *Rotation gestures*: rotating your hand [22] or making clockwise or counter-clockwise gestures can be used for tasks such as rotating or resizing objects.

Candidate gestures to be recognized by a radar placed on a **horizontal** surface, such as a ceiling [20], should be easily recognizable from the top and include:

1. *Horizontal gestures*: any gesture belonging to the aforementioned categories can represent candidates provided that they are exposed horizontally enough [25].
2. *Finger counting gestures*: these gestures, where the number of fingers extended is interpreted as a command or input, can be recognized provided that they are exposed horizontally, not vertically.
3. *Gesture sequences*: complex sequences of gestures, which can be customized to perform specific actions or trigger events, can also be recognized by advanced ceiling radars.

Similarly to gestures detected from the ceiling, gestures that can be recognized by a floor sensor depend on the capabilities of the radar itself and the horizontal exposure, such as:

1. *Foot gestures*: gestures made with the feet, especially those that are close to the surface, can include tapping, kicking, or specific foot patterns to control devices, navigate through interfaces, or play games.
2. *Leg gestures*: gestures of the legs, such as lifting or extending them in specific patterns, can be used for tasks like selecting options from a menu, controlling virtual characters, or triggering actions in a virtual environment.
3. *Whole body gestures*: some floor radars are able of detecting larger-scale gestures of the body, such as leaning, stepping, or jumping. These gestures can be utilized for immersive experiences in virtual reality applications, fitness tracking, or interactive installations.
4. *Dancing gestures*: dance movements and choreographic gestures, allow users to interact with music or visualizations through their dance motions. This can be used for entertainment purposes, dance training, or artistic expression.
5. *Pressure sensing gestures*: some floor sensors are able of detecting variations in pressure distribution, allowing them to recognize gestures such as shifting weight from one foot to another, or applying pressure in specific areas. These gestures are more challenging to recognize by radars which are not sensitive to pressure but can detect acceleration variations, such as when jumping, hitting, or foot tapping.

Finally, radars placed on an interaction surface **in front** of the end-user probably offer the widest range of gestures candidates, which include:

1. *Hand gestures*: such gestures, such as waving, pointing, or making specific shapes, symbols, or letters with the hands, can be detected by frontal radars [13]. These gestures are often used to control devices found in ambient environments, interact with virtual interfaces, or navigate through menus.
2. *Finger gestures*: gestures of individual fingers or combinations of fingers can be recognized by frontal radars, provided that their vertical exposure is wide enough. For example, pinching, tapping with specific fingers, or making gestures like the peace sign can be interpreted as commands or inputs.

3. *Palm gestures*: Gestures involving the hand palm, such as open-handed gestures, palm rotations, or covering and uncovering the palm, are among the best candidates for gesture-based interaction [33, 28].
4. *Arm gestures*: gestures of the arms [17], such as raising, lowering, or extending them in specific directions, can be recognized by frontal radars. These gestures can be used for tasks like controlling virtual objects, or adjusting settings (*e.g.,* increase or decrease the sound level).
5. *Head and shoulders gestures*: frontal radars can also detect gestures of the head, such as nodding, shaking, or tilting it in different directions provided that their vertical exposure is large enough to differentiate the gesture variations. Same for shoulder gestures [32].

1.6 Conclusion

In conclusion, radar-based gesture interaction represents a paradigm shift in human-computer interaction, offering a seamless and intuitive way to engage with digital systems. By examining this technology from multiple orientations, we should gain a better understanding of its capabilities, applications, and implications. In particular, we should be able to better understand which gesture candidates are recognized with accuracy enough in various orientations to warrant their inclusion in a gesture set.

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