FidMark: A Fiducial Marker Ontology for Semantically Describing Visual Markers

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Abstract. Fiducial markers are visual objects that can be placed in the field of view of an imaging sensor to determine its position and orientation, and subsequently the scale and position of other objects within the same field of view. They are used in a wide variety of applications ranging from medical applications to augmented reality (AR) solutions where they are applied to determine the location of an AR headset. Despite the wide range of different marker types with their advantages for specific use cases, there exists no standard to decide which marker to best use in which situation. This leads to proprietary AR solutions that rely on a predefined set of marker and pose detection algorithms, preventing interoperability between AR applications. We propose the FidMark fiducial marker ontology, classifying and describing the different markers available for computer vision and augmented reality along with their spatial position and orientation. Our proposed ontology also describes the procedures required to perform pose estimation, and marker detection to allow the description of algorithms used to perform these procedures. With FidMark we aim to enable future AR solutions to semantically describe markers within an environment so that third-party applications can utilise this information.

Keywords: fiducial marker · ontology · augmented reality · pose estimation

Resource type	Ontology
License	CC BY-SA 4.0
URL	`https://purl.org/fidmark/`
Documentation	`https://fidmark.openhps.org/1.0/en/`
Demonstrator	`https://fidmark.openhps.org/application/`
Repository	`https://github.com/OpenHPS/FidMark/`
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1 Introduction

In computer vision applications, or more specifically augmented reality (AR) solutions, superimposing virtual objects in real-world scenes poses a challenge due to the lack of an accurate absolute position of the camera in the physical world.

Various methods can be employed, such as creating virtual anchors based on visual features [7], anchoring these virtual objects to an absolute location based on GPS or indoor positioning systems [33] or using predefined visual landmarks that can be used as a spatial reference [26]. These landmarks, often referred to as fiducial markers, are used to determine the position and orientation (i.e. a *pose*) of an image sensor detecting these markers within its field of view [25]. While markers can be used to track the position of a camera or AR device, they can also help to position and scale virtual objects relative to these markers.

Applications using fiducial markers to determine a pose need to be able to detect and map the markers to their known position and orientation, which often requires a proprietary local or cloud-based database to retrieve this contextual information. In addition, the vast variety of available marker types [20,23], each with their own set of properties that are required to detect and identify these markers, make it difficult to generically define the contextual information of a marker.

Looking at existing ontologies and vocabularies, the Digital Imaging and Communications in Medicine (DICOM) ontology [19] describes fiducial markers and identifiers used within the medical field for use cases such as providing a visual landmark when performing radiology. Despite of being a domain-specific ontology, DICOM defines some generic concepts that are also found in fiducial markers for other applications. In the Machine-to-Machine Measurement (M3) Lite ontology, a description for the concept of a `m3lite:TagDevice` and tag device types such as a QR code or barcode are provided [12]. However, similar to the Schema.org vocabulary [11] also providing concepts for a generic barcode, it does not provide concepts for identifying different types of markers or individual markers for a specific type of marker.

When focusing on AR applications, fiducial markers are used for position and orientation tracking using both outside-in [35] and inside-out tracking [10]. With inside-out tracking, markers are placed within the physical environment and tracked by an AR device's image sensor. On the other hand, in outside-in tracking, markers are placed on a moving object such as a person, with fixed image sensors in the physical environment tracking these markers. Different marker types and variations exist that perform better depending on the environmental conditions such as scanning distance, scanning angle, light conditions or motion blur [5]. This makes it impossible to rely on a single type of fiducial marker when used for AR applications.

In order to support the interoperability of computer vision and augmented reality applications using fiducial markers, we propose the FidMark ontology that can semantically describe these individual markers as well as provide an annotated description on various marker types. Our ontology can describe the main properties of markers and their pose within a defined reference space. Being able to describe fiducial markers and their position within a physical space allows multiple actors to understand the semantics of a visible marker and even allows them to detect these markers. This enables future interoperability between augmented and mixed reality applications by describing a common reference frame relative to a marker.

We start by presenting our design approach and several design goals for our FidMark ontology in Sect. 2. The design of the FidMark ontology with some examples is introduced in Sect. 3. Finally, a validation of the FidMark ontology and discussion of a demonstrator application in Sect 4 is followed by some conclusions and plans for future work.

2 Approach and Methodology

Our design approach for the requirements of our ontology is based on the Linked Open Terms (LOT) methodology [31]. Due to the already existing ontologies for describing fiducial markers in medical sciences [19], we decided to focus on fiducial markers used within the domain of computer vision (CV), primarily for markers which can be used for pose estimation [27] that obtains both a position and orientation. We started by analysing the different existing types of markers for applications within the domain of computer vision [20,23]. Next, using this set of different markers with their use cases for different scenarios and environmental conditions, we have listed a set of use cases, design goals and required data for each type of marker.

Based on the marker analysis and their data properties, we determined the common attributes and properties of each marker. Two of the main common properties of each marker are the inclusion of an identifier and its ability to be used to determine a pose. Depending on the type of encoding and error correction, these markers use a dictionary that contains a set of possible identifiers that can be encoded within the marker. Computer vision applications that want to detect these markers should know which dictionary is used to perform the correct identification.

For the terminologies used for these data properties, we relied on common terms used within academic research as well as the standardisation of fiducials and their intrinsic properties for various domains [17,16,15,14]. We also investigated frameworks and libraries that scan for markers and the variable names that were used for expressing the data [4,1].

2.1 Design Goals

In the following, we list the main design goals (DG1–DG7) we aim to achieve with our ontology. These goals will be used to scope our ontology to the required functionality and serve as a basis for the implementation and validation of the FidMark ontology.

DG1 *Enable the retrieval of a list of supported markers*: This design goal should enable applications to retrieve individual markers that are detectable by the hardware and software.

DG2 *Enable the retrieval of markers using the identifiable information*: This design goal should enable applications to retrieve marker information based on visually detectable and identifiable information such as the marker identifier or encoded data.

DG3 *Enable the description of a marker with a non-standard symbology*: In order to enable scalability for the ontology and marker types, variations on the symbology should be possible.

DG4 *Enable pose estimation of markers based on their description without ambiguity*: Two actors, each with their own marker detection implementation should be able to use all the available information to provide equal pose estimation for the same semantically described marker.

DG5 *Enable the positioning of virtual objects relative to a marker*: It should be possible to superimpose virtual objects around a marker, without having to to know where the marker is located in the physical space.

DG6 *A marker should be used as an engineering reference frame or image coordinate reference system [16,15]*: The marker should be used as a landmark when performing visual positioning. This entails that the marker should enable absolute pose estimation for an image sensor.

DG7 *Facilitate the integration of computer vision markers in frameworks*: Having a semantic description of a marker is required to decide what algorithms to use to detect and identify the marker. However, to further facilitate the detection, information should be available to decide what marker types to use and how to integrate them into a computer vision framework without having to perform a manual mapping. This in turn also relies on design goal DG4 that requires the detection of markers without ambiguity, as it also means that the description of a fiducial marker should not be framework dependent.

Each design goal poses its challenges. While we can determine multiple common properties for each marker type in our ontology design as shown later in Sect. 3.1, ensuring that markers can be described without ambiguity such as different marker origins (e.g. using the centre of the marker as the origin of its position) also requires a more detailed description of the necessary detection processes.

3 Ontology Design

As outlined in our approach, the proposed FidMark ontology is primarily designed to describe fiducial markers used in augmented reality (AR). However, one of our design goals is to ensure that our ontology can easily be extended and aligned to also describe fiducial markers for other domains.

In order that markers can be used for pose estimation, we have built our ontology on top of the generic Positioning System Ontology (POSO) [40] that can already describe visual landmarks with their spatial location and orientation. POSO allows us to add both *absolute* positions and *relative* positions to spatial objects, enabling the positioning of (virtual) objects relative to a marker. We expanded POSO to support different types and classifications of fiducial markers, their identifiers, image descriptors and calibration data. In addition, we also added two procedures to differentiate between markerless [28] and marker-based pose estimation via the `poso:PositioningTechnique` concept.

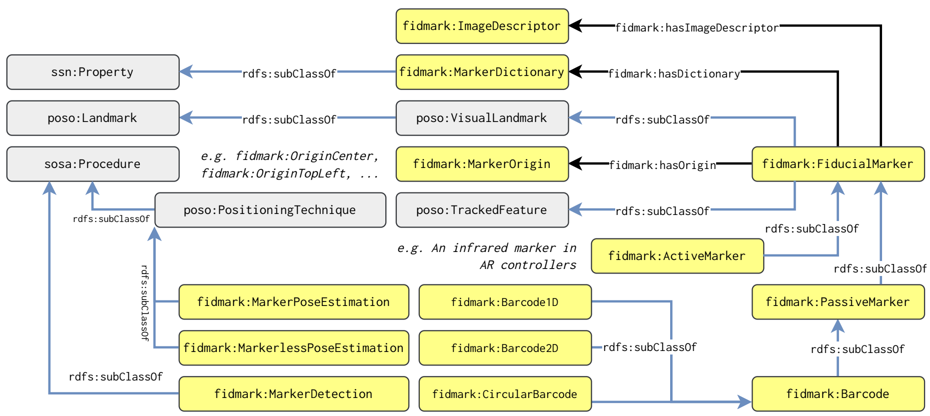

Fig. 1: FidMark main classes

The main classes of our FidMark ontology are illustrated in Fig. 1. We make a clear classification of active and passive markers [29] as this represents the major difference between different types of markers. We further subclassed passive markers into barcodes that can encode information such as an identifier. In addition to these main classes, we currently provide over 30 different types of markers as subclasses of the fiducial marker class[1], such as reacTIVision [21] or CCTag [5].

With our ontology we aim to describe different markers, their setup and their position relative to a certain reference space. The basic architecture and a use case for our ontology is demonstrated in Fig. 2. We describe markers, their identifier, position and orientation using the combination of FidMark and POSO. FidMark handles the description of the markers while POSO is used to describe the markers' absolute and relative position as visual landmarks. AR-capable devices with access to this description can synchronise their reference frame due to the common description. Any virtual object placed relative to these markers can again use the generality of POSO to indicate its relative position.

In our ontology, each type of fiducial marker is annotated with additional metadata describing the markers' visual and functional properties such as their shape, colour and encoding method. When available in OpenCV [4], we also

[1] For more information about the ontology profile and ontology statistics, please check the online documentation.

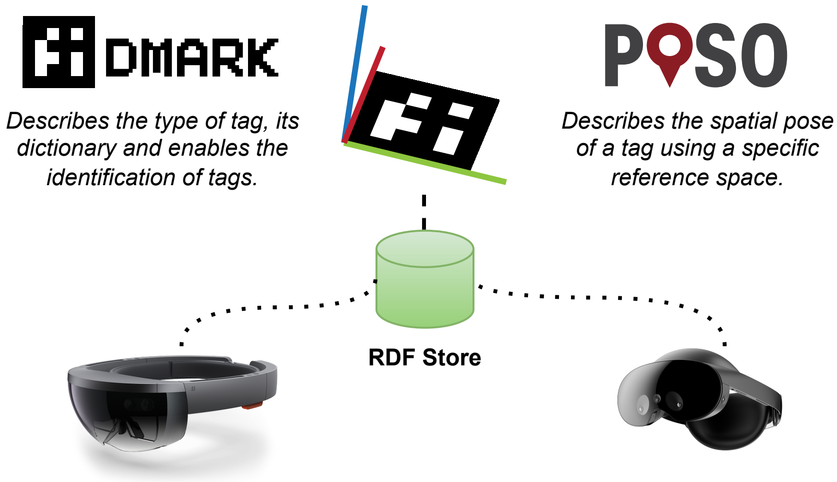

Fig. 2: Basic usage of FidMark together with the POSO ontology

provide the dictionary names of markers as they are available in OpenCV to facilitate the development as outlined in design goal DG7.

To demonstrate the generality of FidMark for applications outside the domain of augmented reality, we provide the `fidmark-dicom` alignment ontology to align fiducial markers and POSO with the Digital Imaging and Communications in Medicine (DICOM) ontology [19] in our supplemental material.

3.1 Properties and Terminologies

Fiducial markers have a set of properties that are subproperties of properties on `sosa:FeatureOfInterest` from the Sensors, Observations, Systems and Actuators (SOSA) ontology [18]. They define how the marker should be detected, decoded and mapped to its location within the physical space. With fiducial markers being used to determine the relative translation, scale or orientation of visual objects within the field of view. The object and data properties we added to our ontology are also chosen to enable this description.

We provide the `:hasOrigin` predicate and `:MarkerOrigin` property to indicate the position origin on the marker itself. This origin determines the 2D or 3D location on the fiducial marker. An origin description is required to determine the accurate translation when performing relative positioning from virtual objects relative to the marker.

– **dictionary**: A set of marker identifiers that are available using a specified encoding scheme. A dictionary is also referred to as a *marker symbology* or *marker family* [17]. This encoding scheme can be generalised to both binary encoding in barcodes as well as the encoding with active markers such as infrared markers [37].

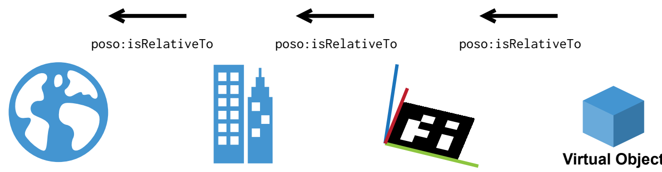

Fig. 3: Relative positioning of virtual objects and markers

- **origin**: The origin of the marker is an important design requirement in order to determine the relative orientation and translation to the marker. Our `:hasOrigin` predicate and `:MarkerOrigin` property are based on the OpenCV *pattern*. In Fig. 3, we illustrate how a virtual object is positioned relative to the `:MarkerOrigin`. The marker itself can be positioned relative to a known coordinate reference system or relative to other objects such as a room or building.
- **dimensions**: The known dimensions of a marker can be used to determine its scale. Our ontology supports the specification of both, a marker's width and height to support rectangular markers such as AprilTag [30].
- **hamming distance**: The minimum hamming distance between two codes, represented by the minimum number of bits that must be changed in one tag's code to reach another tag's code.
- **image descriptor**: The marker image descriptor links to an image URI or a Base64 representation of the image. Alternatively, the image descriptor can be described as a processed descriptor for natural feature tracking [3] as illustrated in Fig. 4.
- **identifier**: A numeric identifier that can uniquely identify a marker from a (pre-)defined *dictionary*. The identifier is (part of) the encoded data.
- **data**: Other than an identifier, some marker types allow the encoding of other types of binary data. An example of such a marker is a QR code, which can be used for both, pose estimation as well as the encoding of binary data.
- **codes & marker bits**: Frameworks with no prior knowledge of the concept of a dictionary or how it is computed require a list of all available codes that can be encoded with the available `:markerBits` and error correction.

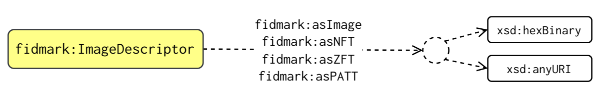

Fig. 4: Image descriptor usage for markers

For a complete list of properties, please refer to the online documentation in our supplemental material also providing marker-specific object and data properties[2].

[2] `https://openhps.github.io/FidMark/1.0/en/`

3.2 Procedures

The SOSA and POSO ontology both use *procedures* to indicate a process of computing data in a certain way. In Fig. 1, we already listed procedures for marker detection and pose estimation. However, in order to reduce the chance of ambiguity in pose estimation [36], we also extended POSO to add the most common Perspective-n-Point (PnP) pose computation algorithms used in existing AR and Computer Vision frameworks [22,24,6,8].

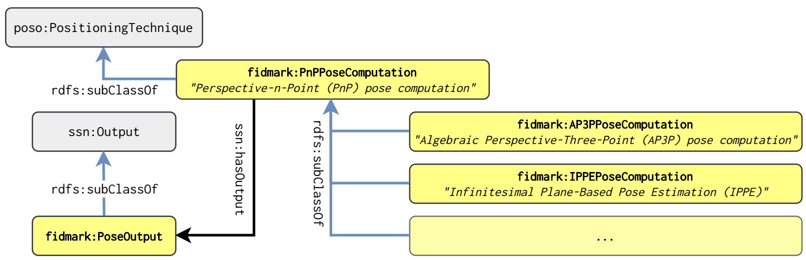

Fig. 5: Pose computation procedures in the FidMark ontology

The use of the PnP pose computation algorithms and the `:PoseOutput` associated with these procedures is illustrated in Fig. 5. Similar to the examples in the SOSA ontology, this output can be linked to a SHACL [13] shape to validate the output of an algorithmic procedure, which in this case would include a position and orientation.

3.3 Usage

In the following, we illustrate how FidMark can be used to describe markers in various scenarios. In Listing 1, we provide an example of an ArUco marker [9] described using our ontology. FidMark comes with a set of predefined dictionaries which in this example uses the original ArUco dictionary with a minimum hamming code distance of 0 and a maximum of 1024 identifiers. In addition to the marker information, the position and orientation are described. Computer vision applications can utilise this information to detect the marker and determine its position within 3D space. To avoid ambiguity, the origin of the origin of any object's position is positioned relative to the centre of the marker using the `fidmark:hasOrigin` predicate. The position of the marker is described using a well-known text (WKT) representation of a geo-referenced position [2].

Using the POSO ontology, we can utilise the `fidmark:FiducialMarker` visual landmark as a reference frame to position other objects. In Listing 2, we demonstrate how a simple virtual object is positioned relative on top of the AruCo marker from Listing 1 by indicating that it is positioned relative to

```
:marker-1 a fidmark:ArUco ;
  fidmark:hasDictionary fidmark:DICT_ARUCO_ORIGINAL ;
  fidmark:markerIdentifier 94 ;
  fidmark:hasHeight [ a qudt:QuantityValue ;
      qudt:unit unit:MilliM ; qudt:numericValue "100"^^xsd:float ] ;
  fidmark:hasWidth [ a qudt:QuantityValue ;
      qudt:unit unit:MilliM ; qudt:numericValue "100"^^xsd:float ] ;
  fidmark:hasOrigin fidmark:OriginCenter ;
  poso:hasPosition [ a geo:Point, poso:AbsolutePosition ;
    ogc:asWKT "POINT Z(...)"^^ogc:wktLiteral ] ;
  poso:hasOrientation [ a poso:QuaternionOrientation
    poso:xAxisValue [ ... ] ; poso:yAxisValue [ ... ] ;
    poso:zAxisValue [ ... ] ; poso:scalar [ ... ] ] .
```

[a] http://purl.org/fidmark/
[b] http://purl.org/poso/
[c] http://qudt.org/schema/qudt/
[d] http://qudt.org/vocab/unit/
[e] http://www.opengis.net/ont/geosparql#

Listing 1: Example ArUco marker using the `fidmark`[a], `poso`[b], `qudt`[c], `unit`[d] and `ogc`[e] prefixes

this object. As a demonstrator, we utilise the Ontology for Managing Geometry (OMG) and File Ontology for Geometry formats (FOG) to describe the 3D geometry model that will be superimposed [38].

```
:object a sosa:FeatureOfInterest ;
   rdfs:label "A virtual cube"@en ;
   poso:hasPosition [ a poso:RelativePosition ;
      poso:isRelativeTo :marker-1 ;
      poso:xAxisValue [ ... ] ; poso:yAxisValue [ ... ] ;
      poso:yAxisValue [ ... ] ] ;
   poso:hasPosition [ a poso:EulerOrientation ;
      poso:isRelativeTo :marker-1 ;
      poso:pitch [ ... ] ; poso:roll [ ... ] ; poso:yaw [ ... ] ] ;
   omg:hasGeometry [ a omg:Geometry ;
      fog:asGltf "https://.../Cube.gltf"^^xsd::anyURI ] .
```

[a] http://www.w3.org/ns/sosa/
[b] https://w3id.org/omg#
[c] https://w3id.org/fog#

Listing 2: Example relative positioning using the `sosa`[a], `omg`[b] and `fog`[c] prefixes

By enabling relative positioning with the marker, we satisfy design goal DG6 which requires the marker to be used as an engineering or image frame of reference. A marker can also be described without a position and orientation in the physical world, in which case it only acts as an engineering frame of reference for other objects positioned relative to the marker.

Some tags rely on the training of image data, preventing the possibility of only describing a marker using a dictionary and a simple identifier. To enable the description of fiducial markers that do not encode information or identifiers, we provide a `:hasImageDescriptor` predicate and `:ImageDescriptor` class. The image descriptor can be expressed as a raw image or pattern such as natural feature tracking (NFT) [3].

Tracked Markers While previous examples used the description of markers relative to the markers with a fixed position, fiducial markers are also used for outside-in tracking [35] where stationary image sensors track the position of moving markers. The POSO ontology can be used to observe changes in the position of tracked markers and Listing 3 illustrates a marker with an observable absolute position.

```
:marker-1 a fidmark:ArUco ;
    poso:hasPosition :marker-1-position ;
    poso:hasOrientation :marker-1-orientation .

:marker-1-position a poso:AbsolutePosition ;
    rdfs:label "Position of Marker 1"@en .
:marker-1-orientation a poso:Orientation ;
    rdfs:label "Orientation of Marker 1"@en .

:position-1701946800 a sosa:Observation ;
    sosa:hasFeatureOfInterest :marker-1 ;
    sosa:observedProperty :marker-1-position ;
    sosa:resultTime "2023-12-07T11:00:00+01:00"^^xsd:dateTimeStamp ;
    sosa:hasResult [
        ...
    ] .
```

Listing 3: Marker with multiple tracked poses

4 Ontology Validation and Demonstrator

Our FidMark ontology has been validated using the OntOlogy Pitfall Scanner [32] and a set of SPARQL queries that answer the design goals DG1–DG7 listed earlier in our methodology. In addition, we created a demonstrator web application that can serialise and deserialise markers and virtual objects positioned relative to these markers. The web application will then use the deserialised information to superimpose virtual objects on top of markers detected with js-aruco2[3]. Our application[4] superimposing a 3D object ten centimetres above

[3] https://github.com/damianofalcioni/js-aruco2

[4] https://openhps.github.io/FidMark/application/

an ArUco marker with identifier 10 in a specific dictionary as shown in Fig. 6. This demonstrator was created using the OpenHPS framework [39] for aiding with the positioning and serialisation.


```
:marker-1 a fidmark:ArUco ;
  fidmark:markerIdentifier 10 ;
  fidmark:hasOrigin fidmark:CenterOrigin ;
  fidmark:hasDictionary fidmark:DICT_MIP_36h12 ;
  fidmark:hasWidth [ a qudt:QuantityValue ;
    qudt:unit unit:MilliM ;
    qudt:numericValue "200"^^xsd:double ] ;
  fidmark:hasHeight [ a qudt:QuantityValue ;
    qudt:unit unit:MilliM ;
    qudt:numericValue "200"^^xsd:double ] .

:earth a sosa:FeatureOfInterest ;
  poso:hasPosition [ a poso:RelativePosition ;
    poso:isRelativeTo example:marker-1 ;
    poso:xAxisValue [ ... ] ;
    poso:yAxisValue [ ... ] ;
    poso:zAxisValue [ a qudt:QuantityValue ;
      qudt:unit unit:CentiM ;
      qudt:numericValue "10"^^xsd:double ]] ;
  omg:hasGeometry [ a omg:Geometry;
    fog:asGltf ".../earth.gltf"^^xsd:anyURI ] .
```

Fig. 6: Demonstrator web application showing two markers with different dictionaries and two virtual objects positioned relative to these markers

Every SPARQL query is based on the design goals listed in Section 2.1. We have used the Pellet reasoner [34] on top of our ontology and an example dataset[5] which was created to test the queries. Fiducial markers have multiple subclasses that we query for all square fiducial markers in Listing 4 (lines 1–4) using the `:shape` annotation property on every subclass of `:FiducialMarker`. Similarly, other annotation properties such as the colours used within the marker can be used to determine the appropriate marker type for the available hardware.

Use cases where the ontology is applied to discover the appropriate marker type can also make use of the available dictionaries or marker families for markers that support identification. To demonstrate a scenario where we want to search for an ArUco dictionary that supports at least 150 markers, we can perform a similar query as shown in Listing 4 (lines 6–11). Each known dictionary will have listed its dictionary size, bit size and possible error correction methods.

[5] `https://github.com/OpenHPS/FidMark/blob/main/examples/virtual_objects.ttl`

```
SELECT ?markerType WHERE {
    ?markerType rdfs:subClassOf* fidmark:FiducialMarker .
    ?markerType fidmark:shape "Square"@en .
}

SELECT ?dictionary ?size WHERE {
    ?dictionary a fidmark:MarkerDictionary .
    ?dictionary fidmark:supportedMarker fidmark:TopoTag .
    ?dictionary fidmark:dictionarySize ?size .
    FILTER(?size >= 150)
}
```

Listing 4: SPARQL query to retrieve all square markers and another SPARQL query to retrieve all predefined TopoTag dictionaries that support more than 150 unique tags

On lines 1–7 of Listing 5 we illustrate a query to obtain a pose from an ArUco marker with identifier `19`. Optionally, a dictionary can be provided when multiple ArUco markers are available with different dictionaries. When an AR application detects a marker, it should retrieve all the information including the virtual objects placed relative to this detected marker. An example query is provided in Listing 5 on lines 9–16 where we query for all virtual objects with a `poso:RelativePosition` that is positioned relative to the QR code using the `poso:isRelativeTo` predicate.

```
1  SELECT ?position ?orientation WHERE {
2      ?markerType rdfs:subClassOf* fidmark:ArUco .
3      ?marker a ?markerType .
4      ?marker fidmark:identifier 19 .
5      ?marker poso:hasPosition ?position .
6      ?marker poso:hasOrientation ?orientation .
7  }
8
9  SELECT ?object WHERE {
10     ?object a sosa:FeatureOfInterest .
11     ?object omg:hasGeometry ?geometry .
12     ?object poso:hasPosition ?position .
13     ?position poso:isRelativeTo ?marker .
14     ?marker a fidmark:QRCode .
15     ?marker fidmark:markerData "001122334455"^^xsd:hexBinary .
16 }
```

Listing 5: SPARQL query to retrieve marker pose based on type and identifier and a SPARQL query used in the web application to retrieve all virtual objects placed relative to a detected marker

5 Conclusion and Future Work

In the presented work, we proposed the FidMark ontology for describing visual fiducial landmarks. FidMark can be used to semantically describe and publish the type and position of fiducial markers in the physical world. Augmented reality (AR) applications can use this description to detect, identify and position themselves or other virtual objects that are placed relative to the markers.

Our ontology is built upon the generic Positioning System Ontology (POSO) supporting the generic description of the absolute and relative position and orientation of markers and objects placed relative to these markers. Despite focusing on computer vision fiducial markers, we also provide an alignment with the DICOM ontology for fiducial markers in healthcare applications.

Based on seven design goals (DG1–DG7), we validated our ontology using a set of example SPARQL queries on top of our ontology and a generated test dataset. We also created an open-source demonstrator AR application that is available online and shows virtual objects relative to markers described with the FidMark ontology. This AR application demonstrates how the FidMark ontology can help to build interoperable AR applications that can use a commonly described reference frame.

Future work will primarily focus on expanding the annotation of marker types and dictionaries. While our ontology currently includes the most prominent AR fiducial markers according to recent surveys, we plan to expand FidMark with additional fiducial marker types based on other academic research that was not covered in the survey papers used for our initial release. Using these new marker types we will also expand the available procedures to detect and perform pose estimation for different types of markers, based on the different visual features offered by the markers. Finally, we will also develop additional FidMark use cases and examples to facilitate the synchronisation of reference spaces between multiple AR devices.

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