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An Ontology for Smart Home Design

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***Abstract*—Smart homes are becoming very fashionable. However, the construction of smart homes is still a developing industry. Thus, there are currently no standard criteria for defining smart homes. And since there is also no standard design model for smart homes, this study develops an ontology to formalise the design of smart homes. The aim of this smart home ontology is to provide useful information to DIY enthusiasts all the way up to architects to model a Smart Home. An iterative process was used to develop this smart home ontology. Existing ontologies and literature were used to gain a better understanding of how to model the ontology. The resulting smart home ontology can help to understand better the structure or framework of a smart home and how all the devices are interconnected and how smart homes can make peoples' everyday lives easier as well as reducing the carbon footprint.**

Keywords—Ontology, Smart Home, Renewable Energy, Smart Devices, Protégé.

I. Introduction

Due to the decrease in the cost of technology [1], smart homes are becoming more popular globally [2]. Currently, smart homes are still a developing industry; thus there are no worldwide standards that clearly define the criteria of a smart home. The term 'smart home' appeared only recently [6]; it is a synonym for automated homes or intelligent buildings. A smart home incorporates electronic equipment that monitor all components of the home. The smart home control devices can monitor the internal environment and activities that are undertaken whilst occupied.

The rise in the costs of energy costs have increased the demands for energy efficient systems and an even greater increase in the demand for energy saving solutions [11]. Thus the emergence of smart homes to reduce energy consumption with the added benefit of automating everyday tasks, as well as the ease of use and convenience of performing daily tasks at the tip of your fingers. A smart home is only as effective as its design [12].

A good design is pivotal to the overall effectiveness and efficiency of the smart home as a whole [12]. Currently, there is no standard for modelling smart homes. Thus, many examples in literature were reviewed, and helped guide this research, in terms of information representation and reuse of vocabulary. The main focus of the ontology proposed in this study is the design of a smart home with the incorporation of renewable energy sources to achieve the overall goal of creating an energy saving solution. The ontology takes into account the electricity from the national power grid as well as renewable energy sources. The smart home aspect is comprised of various smart devices that are able to communicate over a network and perform device specific tasks which can be controlled via the network. To incorporate the energy saving aspect some smart devices will use renewable energy. This resulting smart home ontology provides useful knowledge and information to individuals who wish to design an energy efficient solution with the added convenience of an automated home as well as reducing long term costs.

The aim of the smart home ontology is to provide useful information to DIY enthusiasts all the way to architects is to model a smart home as well as help reduce one's carbon footprint by incorporating renewable energy into the smart home design. The Ontology Development (OD101) methodology [13] was used to develop the smart home ontology. The OD101 prescribes an iterative process for developing ontologies.

The rest of the paper is organised as follows.: Section 2 provides an insight into existing related work, Section 3 outlines the materials and methods used to form the ontology, Section 4 describes the modelling of the ontology which includes vocabulary of the domain, classes, properties, list of axioms, first order logic and description logic of the domain. Section 5 entails the implementation of the ontology that includes the dataset and the computer used, with the results. Section 6 provides a conclusion to the ontology.

II. Literature Review

The aim was to focus the target smart home design ontology in two main domains, namely, design of smart homes and energy saving homes. Information about these domains were acquired from related articles [1][2][3][4][5][6][7].

In [1], an ontology for the design of home automation is presented. The ontology describes what devices are used typically in home automation, taking into account the intelligent behaviour of these devices. The interoperation of the devices and the behaviour aspect, as well as the functionality and device states aspects can be used to model the smart home design ontology.

Another paper in [3] is focused on the domain of home energy management systems. Several vendors and manufacturers use different classification methods; thus this ontology aimed to create a standardised classification method to compare home appliances on the basis of how they perform in terms of energy consumption and to analyse comparatively energy consumption by the appliances. The ontology also outlined details of the home appliances such as functions and energy usage. The classification of appliances, with their functions, can be incorporated into the design of the smart home design domain ontology in this study.

The study in [2] explains in detail how to develop and create a Bluetooth based home automation system. The article lists a variety of hardware components needed and software used to make the system functional. The article also mentions why and when a home automation system would be useful or needed. This article gives a good understanding of how devices connect over a network.

The report in [4] speaks about how to set up a smart home. The report explains what hardware components are required and what software can be used. It gives a detailed description of each hardware component and software system that can be used. This report is useful since it outlines the common components that would be found in a smart home and how they all communicate.

In [7], it is proven that the main reason for the use of modern home automation is to save considerable amounts of electricity. According to [6], heating, ventilation and cooling (HVAC) is the leading energy consumption source. This study demonstrates that energy can be saved by switching off the HVAC system and sensing the occupancy and the sleep patterns in a home with sensors and control devices.

It is argued in [5] that smart home control can save up to 40 percent of heating costs (heaters and geysers). The authors in [5] also stated that many homeowners produce their own electricity by means of solar panels mounted on the roof whilst using smart control panels to monitor and distribute the energy when enough energy is generated. Smart home controlled devices also provide homeowners with the energy consumption so that they are more aware of their usage.

III. Methodology

The methodology utilised to develop the ontology is the Ontology Development 101 (OD101); it prescribes an iterative process for building ontology [13]. Other existing ontologies building methods are reported in [10].

A. Data Collection

The major focus of smart home ontology proposed in this study is the energy saving aspect as well as the efficient design of smart homes; therefore, data was gathered from related ontologies in [3][4][14]. Additional data was obtained from Control4's website [14], which is a company that provides smart home solutions. Other relevant information was gathered in [7][8][9]. From the data collected, a list of 142 statements or axioms in natural language were formulated to describe smart home design with emphasis on the energy saving. The 142 statements constitute the theoretical description of the target ontology. Part of the axioms or statements of the domain of smart home design is provided in Table 1.

The axioms of the smart home design domain in Table 1 describe the modes of network connection in a smart home such as wireless, Wi-Fi and Bluetooth (lines 1 to 7 in Table 1); the controllable and uncontrollable objects in a smart home (lines 8 to 12, 15, 16, 37 and 38 in Table 1); examples of smart furnitures such as smart curtain and table (lines 13 and 14 in Table 1); the things that are continuously controlled in a smart home such as light, shutter, temperature, time, pressure, volume and flow regulations (lines 17 to 26 in Table 1); the energy saving solutions in a smart home such as solar and wind energy (lines 27 to 35 in Table 1); the energy saving sources for controllable objects in a smart home (lines 39 to 43 in Table 1).

TABLE IV. Part of Axioms of Smart Home Domain

	Axioms
1	Wireless is a network type.
2	Wi-Fi is a type of wireless technology
3	Wi-Fi has a Wi-Fi standard
4	802.11n is a Wi-Fi standard
5	Bluetooth is a type of wireless technology
6	Bluetooth has a Bluetooth standard
7	Bluetooth5 is a Bluetooth standard
8	A controllable object is a type of building object
9	An uncontrollable object is a type of building object
10	An appliance is a type of controllable object
11	House system is a controllable object
12	Smart furniture is a controllable object
13	Electric curtain is a smart furniture
14	Smart table is part of smart furniture
15	An architectural object is an uncontrollable object
16	Furniture is an uncontrollable object
17	Control functionality is a type of functionality
18	Continuous control is a type of control functionality
19	Light regulation is a continuous control
20	Shutter regulation is a continuous control
21	Temperature regulation is a continuous control
22	Time regulation is a continuous control
23	Pressure regulation is a continuous control
24	Volume regulation is a continuous control
25	Flow regulation is a continuous control
26	Discrete control is a type of control functionality
27	Grid electricity is a type of power source
28	Renewable electricity is a type of power source
29	Solar energy is a type of renewable electricity
30	Wind energy is a type of renewable electricity
31	A solar panel harnesses solar energy
32	Windmill harnesses wind energy
33	Wind energy is stored in a battery
34	Solar energy is stored in a battery
35	A battery capacity sensor monitors the battery
36	A controllable object has an electrical priority
37	A controllable object has a sensor
38	A controllable object connects to a network
39	A controllable object with a high electrical priority is powered by grid electricity
40	A controllable object with a medium electrical priority is powered by grid electricity or renewable electricity
41	A controllable object with electrical low priority is powered by grid electricity or renewable electricity
42	When the battery capacity sensor is 'Low' change the power source to grid electricity
43	When the battery capacity sensor is 'High' change the power source to renewable electricity

B. Formalisation of Ontology

Two logic-based language including Description Logic (DLs) and Web Ontology Language (OWL) are used to formalize the smart home design ontology [15]. DLs enable the formal modelling of knowledge with classes, properties and instances [17]. OWL is a semantic markup language for representing ontologies on the web [16].

IV. Modeling of Smart Home Design Ontology

A. Vocabulary of the domain

The vocabulary of the domain of smart home design constituted of the classes/concepts, properties/roles and individuals/instances was built from the list of axioms on the domain (see part in Table 1). This was done by analysing the axioms and identifying the classes, properties, and instances, provided in Tables 2, 3 and 4, respectively.

TABLE II. Classes of the Smart Home Design Ontology

	Classes		Classes		Classes
1	Cable	28	Wall	55	Flow regulation
2	Internet	29	Wall opening	56	Double valued
3	Bluetooth	30	Fence	57	Mono valued
4	Bluetooth standard	31	Fence opening	58	Triple valued
5	Wi-Fi	32	Horizontal	59	Continuous notification
6	Wi-Fi standard	33	Balcony	60	Discrete notification
7	Ethernet	34	Ceiling	61	State
8	Controllable	35	Terrace	62	Continuous state
9	Uncontrollable	36	Floor	63	Discrete state
10	Smart furniture	37	Building environment	64	Double valued state
11	Appliance	38	Garage	65	Triple valued state
12	Brown good	39	Garden	66	Power source
13	White good	40	Room	67	Grid electricity
14	House system	41	Functionality	68	Renewable electricity
15	HVAC system	42	Control functionality	69	Solar energy
16	Electric system	43	Notification functionality	70	Wind energy
17	Security system	44	Query functionality	71	Battery
18	Grey good	45	Continuous control	72	Battery capacity sensor
19	Fire system	46	Discrete control	73	Electrical priority
20	Camera system	47	Light regulation	74	Building object
21	House system	48	Shutter regulation	75	Sensor
22	Uncontrollable	49	Temperature regulation	76	Network component
23	Architectural	50	Time regulation	77	Network type
24	Furniture	51	Pressure regulation	78	Wired
25	Vertical	52	Volume regulation	79	Wireless
26	Network	53	High priority		
27	Low priority	54	Medium priority		

Table 2 shows 79 concepts of the domain of smart home design that were gathered from the analysis of the axioms of the domain. The concepts in Table 2 are the classes of the smart home design ontology. They are the main terminologies of the domain and constitute a sharable vocabulary for smart home design. In particular, the aspect of energy saving in the smart home ontology has been modelled in Table 2 with concepts such as *Grid Electricity, Renewable Electricity, Solar Energy* and *Wind Energy* in lines 67 to 70.

TABLE III. Instances of Smart Home Design Ontology

	Instances		Instances		Instances
1	Co-axial	22	Dining room	43	Stove
2	Unshielded Twisted Pair	23	Lounge	44	Washing machine
3	Fiber-optic	24	Lobby	45	Geyser
4	802.11n	25	Storage room	46	Pool pump
5	Bluetooth5	26	Laundry room	47	Smart phone
6	low	27	Study	48	Camera actuator
7	high	28	Pool	49	Control panel
8	Switch	29	Pond	50	Light
9	Router	30	Solar panel	51	Motion sensor
10	Access point	31	Windmill	52	Light sensor
11	Server	32	Gaming console	53	Water sensor
12	Up down state	33	Digital media player	54	Weather sensor
13	On off rest	34	Audio equipment	55	Temperature sensor
14	On off state	35	Coffee maker	56	Flow sensor
15	Open close state	36	Computer	57	Pressure sensor
16	Audio sensor	37	Fan	58	Electrical curtain
17	Light intensity state	38	Alarm clock	59	Smart table
18	Flow rate	39	Printer	60	Bathroom
19	Temperature state	40	Television	61	Bedroom
20	Shutter state	41	Freezer	62	Dishwasher
21	Volume level	42	Refrigerator	63	Oven

Table 3 shows the 63 instances of the smart home design ontology gathered from the analysis of the axioms of the domain (see part in Table 1).

TABLE IV. Properties of the Smart Home Design Ontology

	Properties		Properties
1	is a	6	monitors
2	connects to	7	has- a
3	part of	8	make up
4	type of	9	powered by
5	stored in	10	change to

The 10 properties of the smart home ontology are displayed in Table 4. The properties are used to establish relationships between the constituents of the vocabulary of the ontology. The vocabulary of the smart home design ontology constituted of the classes, properties and instances in Tables 2 to 4 were used to represent formally the axioms of the smart home design ontology in the DLs language. Table 5 displays part of the formal representation of the smart home design ontology in DLs.

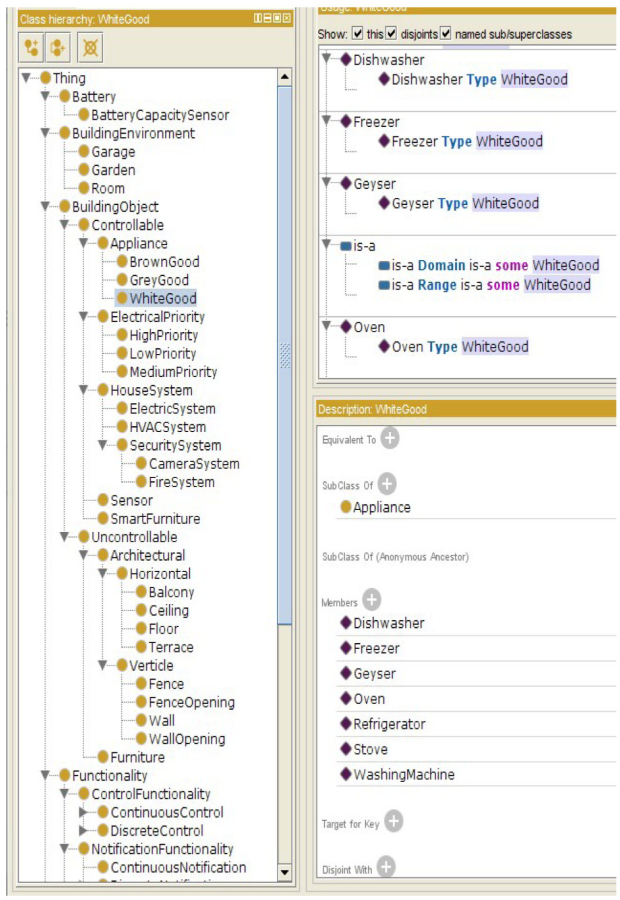

Fig. 1. Screenshot of Smart Home Design Ontology in Protégé

The corresponding DLs modelling of the axioms of smart home ontology in Table 1 are provided in Table 5which provides the DLs modelling of the axioms of the smart home design ontology. The axioms in Table 5 include (1) taxonomies, also called concept inclusions. One can notice them by the inclusion symbols. They represent the inheritance relations between the classes of ontology. (2) class assertions, represented by unary predicatesThey are the instances of classes in the ontology (indexes 3, 7, 13, 14, 31, 32).

TABLE V. PART OF DLS AXIOMS OF SMART HOME DESIGN ONTOLOGY

	DLs Axioms
1	Wireless ⊆ NetworkType
2	Wifi ⊆ Wireless
3	WiFi ⊆ ∀ hasA.WiFiStandard
4	WiFiStandard(802.11n)
5	Bluetooth ⊆ Wireless
6	Bluetooth ⊆ ∀ hasA.BluetoothStandard
7	BluetoothStandard(Bluetooth5)
8	Controllable ⊆ BuildingObject
9	Uncontrollable ⊆ BuildingObject
10	Appliance ⊆ Controllable
11	HouseSystem ⊆ Controllable
12	SmartFurniture ⊆ Controllable
13	SmartFurniture(ElectricCurtains)
14	SmartFurniture(SmartTable)
15	Architectural⊆ Uncontrollable
16	Furniture ⊆ Uncontrollable
17	ControlFunctionality ⊆ Functionality
18	ContinuousControl ⊆ ControlFunctionality
19	LightRegulation ⊆ ContinuousControl
20	ShutterRegulation ⊆ ContinuousControl
21	TemperatureRegulation ⊆ ContinuousControl
22	TimeRegulation ⊆ ContinuousControl
23	PressureRegulation ⊆ ContinuousControl
24	VolumeRegulation ⊆ ContinuousControl
25	FlowRegulation ⊆ ContinuousControl
26	DiscreteControl ⊆ ControlFunctionality
27	GridElectricity ⊆ PowerSource
28	RenewableElectricity ⊆ PowerSource
29	SolarEnergy ⊆ RenewableElectricity
30	WindEnergy ⊆ RenewableElectricity
31	SolarEnergy(SolarPanel)
32	WindEnergy(WindMill)
33	WindEnergy ⊆ ∀ stored-In.Battery
34	SolarEnery ⊆ ∀ stored-In.Battery
35	BatteryCapacitySensor ⊆ ∀ monitors.Battery
36	Controllable ⊆ ∀ hasA.ElectricalPriority
37	Controllable ⊆ ∀ hasA.Sensor
38	Controllable ⊆ ∀ connectsTo.Network
39	Controllable ⊓ HighPriority ⊆ ∃ PoweredBy.GridElectricity
40	Controllable ⊓ MediumPriority ⊆ ∃ PoweredBy(GridElectricity ⊔ RenewableElectricity)
41	Controllable ⊓ LowPriority ⊆ ∃ PoweredBy(GridElectricity ⊔ RenewableElectricity)
42	(Controllable ⊓ MediumPriority) ⊔ (Controllable ⊓ LowPriority ⊓ PoweredBy.RenewableElectricity ⊓ BatteryCapacitySensor(Low)) ⊆ ∃ PoweredBy.GridElectricity
43	(Controllable ⊓ MediumPriority) ⊔ (Controllable ⊓ LowPriority ⊓ PoweredBy.GirdElectricity ⊓ BatteryCapacitySensor(High)) ⊆ ∃ PoweredBy.RenewableElectricity

V. EXPERIMENTAL RESULTS

A. Computer and Software Environment

The ontology was developed in Protégé 5.5.0. Protégé [18], on a Windows 10 computer with the following specifications: CPU Intel Core i5-4690k, 12GB DDR3 1600MHz RAM and 250GB SSD hard drive.

B. Results and Discussions

The DLs axioms of the smart home design ontology (see part in Table 5) are implemented in OWL within protégé. A view of the ontology is displayed in Fig. 1. The class hierarchy of the smart home design ontology is displayed on the left of Fig.1. In particular, highlighted on the left of Fig. 1 is the WhiteGood class. The white good is a type of appliance in the smart home design ontology. It is shown on the right of Fig. 1. The instances of the WhiteGood class include *dishwasher*, *freezer*, *geyser*, *oven*, *refrigerator*, *stove* and *washing machine*.

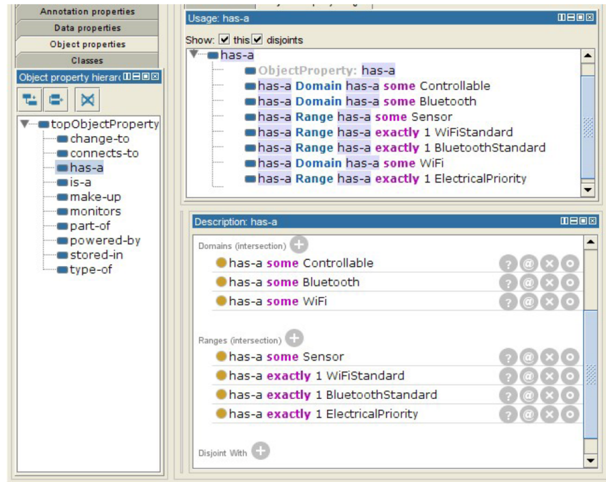

Fig. 2. Properties of Smart Home Design Ontology in Protégé

Fig. 2 depicts on the left-hand side, the property of the smart home design ontology in Protégé. In particular, the property "*has-a*" is highlighted on the left and the axioms which were used in the ontology are listed on the right of Fig. 2. The top part of the right of Fig. 2 also indicates the domains and ranges of the properties "*ha-a*". The domain of a property in an ontology is the class it defines, and its range is the instance or occurrence in the ontology. It is indicated that the domains of the property "*ha-a*" in the smart home design ontology are the classes *Controllable*, *Bluetooth* and *WiFi*, whereas its ranges are the classes *Sensor*, *WiFi Standard*, *Bluetooth Standard* and *Electricity Priority*.

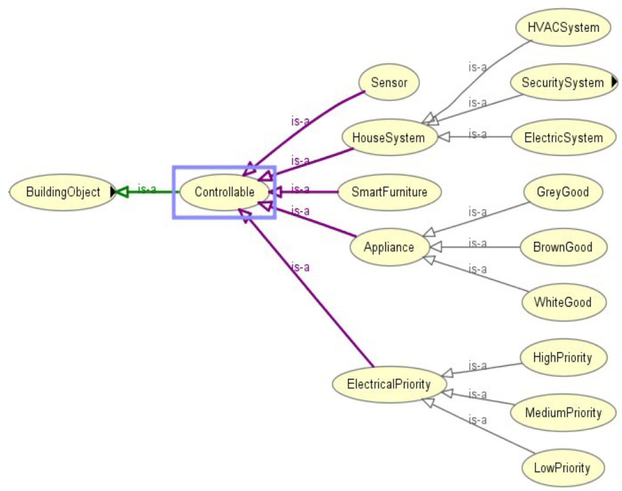

Fig. 3. Taxonomy of Controllables in the Smart Home Design Ontology

The taxonomy of controllable objects in a smart home is displayed in Fig. 3. It is shown that controllable objects in a smart home are grouped into various categories including sensor, house system, smart furniture, appliances and electricity priority. The house system class of controllable object includes subclsasses such as HVAC system, security and electricity systems. The appliance class has subclasses including grey, brown and white goods. The subclasses of the electricy priority class of controllables are high, medium and low priorities. In particular, Fig. 4 displays the instances or individuals of white goods appliances in the smart home ontology.

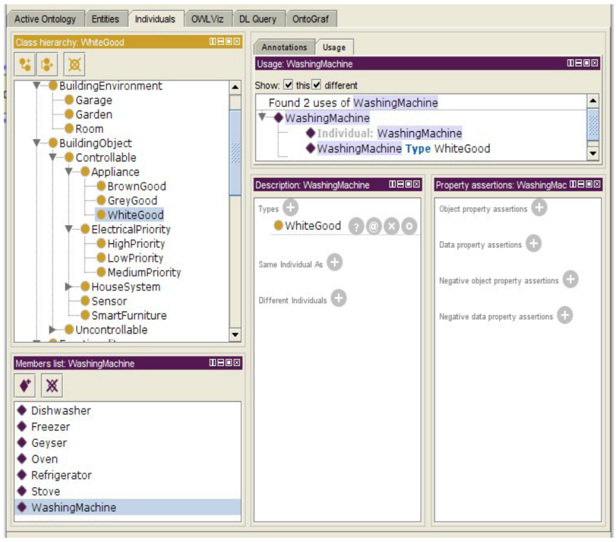

Fig. 4. Instances of White Good in the Smart Home Design Ontology

The *White Good* class is highlighted on the to left of Fig. 4 and its instances are listed at the bottom. Partiticularly, for instance *washing machine* is highlighted and it is indicated in the top right of Fig. 4 that it is indeed an individual or a type of white good in the ontology.

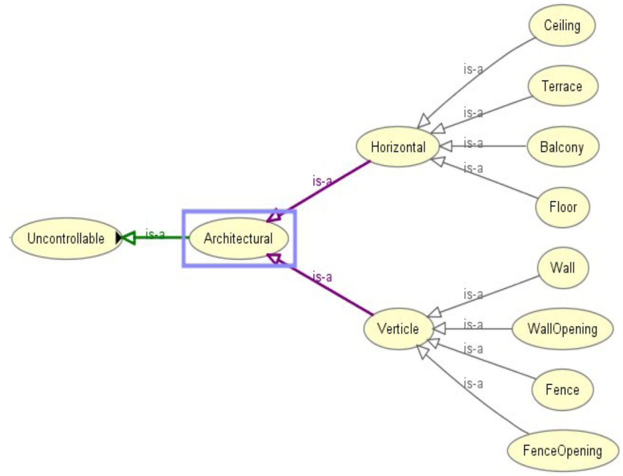

Fig. 5. Architectural Components in the Smart Home Design Ontology

Fig. 5 displays the architectural components of a smart home. These components are uncontrollable and are classified into horizontal and vertical components in the smart home design ontology. The horizontal uncontrollable architectural components of smart home are the ceiling, terrace, balcony, and floor. The uncontrollable vertical architectural components encompass the wall, wall opening, fence and fence opening.

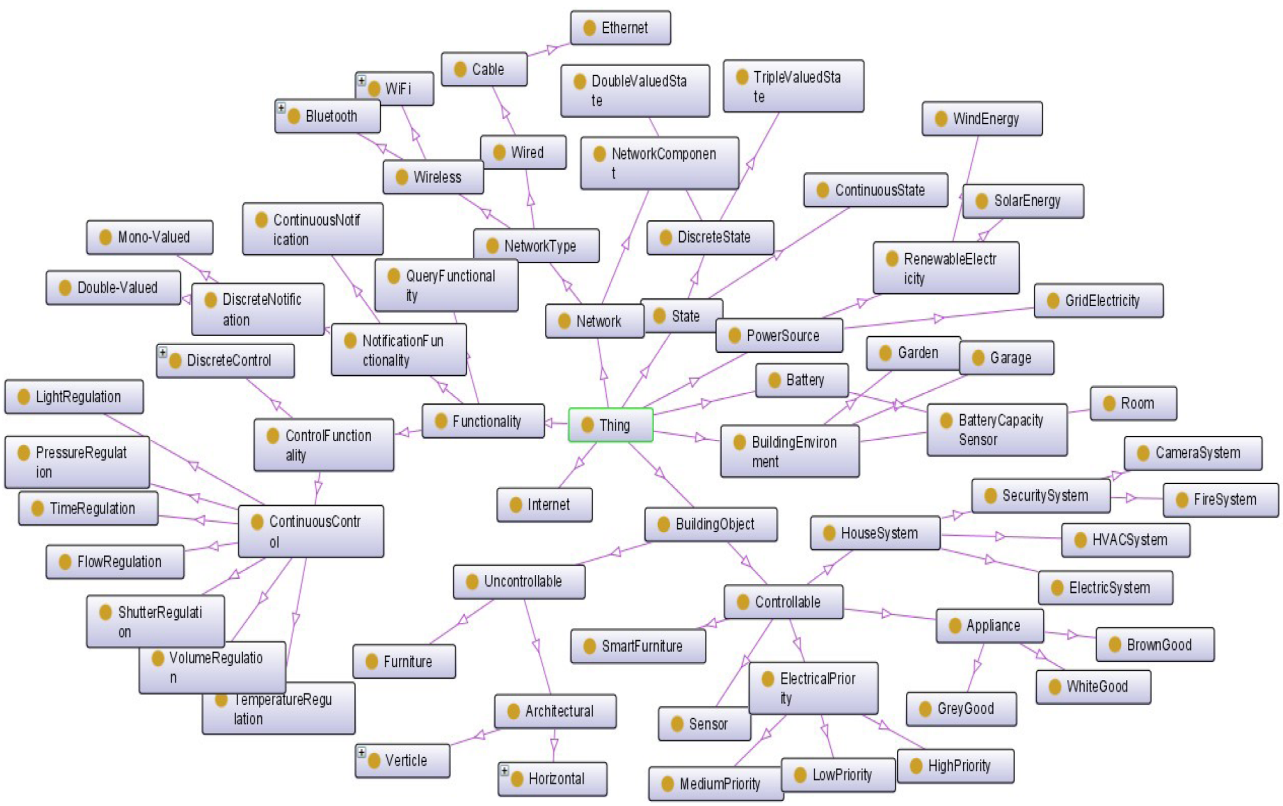

Fig. 6. Graphical Representation of Smart Home Design Ontology

The graphical representation of a view of the smart home design ontology developed in this study is provided in Fig. 6. It can be noticed at the bottom of Fig. 6 that uncontrollable components in a smart home include the architectural components presented in Fig. 5 and the furniture. In general, the classes represented in Fig. 6 are those structured in the taxonomy of classes of the ontolgy on the left of Fig. 1.

VI. Conclusion

An ontology for smart home design was developed in this study with an emphasis on the energy saving facilities. Data was collected from related ontologies and websites as well as published research articles to formalise the smart home design ontology in DLs. The DLs modeling of the smart home design domain was used to develop the ontology OWL within the Protégé ontology editor. The resulting ontology provides useful information such as the controllable and uncontrollable components of smart home, the energy saving solutions such as wind and solar energy, the modes of network connection in a smart home such as Wireless, Wi-Fi and Bluetooth, the things that need continuous control in a smart home such as the light, shutter, temperature, time, pressure, volume, and flow regulations, and many more. The future direction of research would be to investigate the use of Internet of things technologies that leverage the smart home design ontology proposed in this study to develop a ubiquitous computing system for smart home.

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