Smart Wheelchair Sensor Selection Report

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ABSTRACT

This report outlines the selection of sensors that will be used in the smart wheelchair prototype. The relevant literature was reviewed to determine the sensors that have been used in similar applications. Five requirements for the system were defined, against which the sensors found in the literature were assessed. This review and assessment decided that the sensing system would be created from force-sensing resistors (FSRs), optical distance sensors, inertial measurement units (IMUs), and dual temperature and humidity sensors. The specific sensors to be purchased are the Interlink 406 FSR (Interlink Electronics Inc., Camarillo, California, US), Sharp GP2Y0A41SK0F reflective sensor (Sharp Corporation, Osaka, Japan), TE Connectivity HTU21D Temperature & Humidity Sensor Add on Board (TE Connectivity Ltd., Swindon, UK). An IMU has yet to be selected, as the research group may have IMUs already, suppliers have been found for the other sensors, and a purchase list has been compiled for these sensors with a total cost of £385.48 (inc. VAT).

Introduction

This report will outline the selection of sensors that will be used in the smart wheelchair prototype. Examples of seating sensor systems exist in the literature, both intended for wheelchair users and office workers. In these existing sensing systems, many different sensors are used, not all of which are appropriate to the present application. The sensors used in the literature are summarised in Table A1 (provided at the end of this report. A brief discussion of the relevant literature is provided in the following section. In order to determine the sensors that will be used in the prototype smart wheelchair system, five requirements have been defined to aid in evaluating potential sensor technologies.

Sensor Requirements

The requirements for the sensors are summarised below. The sensors must:

1. be capable of measuring 1) pressure, 2) moisture, and 3) temperature at the body-seat interface,
2. be capable of being used to determine/evaluate the sitting posture of the user,
3. not require sensors to be attached to the user in any way,
4. be off the shelf components (to accelerate the hardware development), and
5. have evidence of prior successful use in the literature.

Literature Review

The force-sensing resistor (FSR) is the most popular pressure sensing device found in the literature search. Systems that use only FSRs include those described in [1]–[7]. In addition, these sensors are combined with other sensor types to create mixed sensor systems, such as that recently described by Jeong and Park in [8], that combines FSRs with optical distance sensors. In [8], the authors claim that pressure sensing on the base alone is insufficient to detect trunk rotation. However, Jeong and Park do not investigate if pressure sensing on the backrest can detect the rotation and only compare an optical distance sensing system deployed in the backrest against a pressure sensing system deployed on the seat base. Other papers use pressure sensors deployed in the backrest. However, none of the postures they attempt to classify involve trunk rotation. Therefore, there is a potential avenue for novel investigation, i.e., detecting trunk rotation using sensors deployed in the backrest.

Ultrasonic distance sensors have also been deployed for sitting posture monitoring [9], [10]. However, neither of these systems classify posture with the resolution as that described in [8]. In [9], eight postures are considered compared to the 11 described in [8]. Furthermore, the postures considered in [9] are not as well defined as those in [8]. In [10], the system described only classifies between proper and improper posture. Finally, the scientific quality of the peer-reviewed work presented in [8] is higher than either of the conference papers in [9], [10].

The radio frequency identification (RFID) system of Feng et al. [11] and the FBG system of Tavares et al. [12] are interesting, exhibit good performance, and can also both be used for measuring respiration. However, the RFID system requires tags to be attached to the user's spine and, while this can be used to monitor posture, it does not give pressure information. Both approaches are very new and are not well represented in the literature. For the prototype system, it would be preferable to rely upon technologies that have more evidence to support them.

For microclimate, the systems proposed by Liu et al. [13]–[15] show the most development and promise, especially the system described in [15], which uses a dual temperature and humidity sensor embedded in a small recess in the seat surface. As the sensor is embedded in a recess in [15], this system is more appropriate for the current application than the systems described in [16] and [17], which require sensors to be attached directly to the user's skin. Furthermore, it is noted in [15] that relative humidity depends on temperature, and thus both must be measured in the same location for good performance. Since both temperature and moisture levels must be monitored, it makes sense to utilise a combined temperature and humidity sensor due to the dependence of one quantity on the other. All five papers [13]–[17] show that relativity humidity can be measured to detect moisture levels at the body seat interface.

No systems found in the literature search have investigated pressure and microclimate in the same system. Therefore, the measurement, and combined interpretation, of both represents a potentially novel research avenue.

Inertial measurement units (IMUs) have been used both as instruments attached to the user [18], [19], [20] and as instruments embedded in the seat [21], [22]. These instruments can aid in both classifying postures and measuring the user's activity level.

Sensor Selection

Sensor selection is shown in Tables 2 and 3. First, the available technologies were rated against requirements 3 and 4 (i.e., not requiring sensors to be attached to the user and off-the-shelf components). These are simple binary criteria, and comparing against these first will allow non-compliant technologies to be filtered out, enabling more clarity in assessing viable sensors. Those technologies that meet both criteria 3 and 4 are highlighted in green.

In Table 2, all those sensors that met both criteria in Table 1 are compared to the other three criteria (i.e., 1. Can measure 1) pressure, 2) moisture and 3) temperature at the body-seat interface, 2. Can be used to determine/evaluate the sitting posture of the user, and 5. Has evidence of prior successful use in the literature). Table 2 compiles each technology used in each paper. Each sensor technology may be included in the table multiple times, one for each of the papers in which it is used. The information is structured in this way as different authors may have used the technology differently.

From Table 2, it is clear that no one sensor will be capable of meeting all the requirements on its own.

- Both the BCG and accelerometer do not meet any of the additional requirements and will not be considered further.
- The FSR is the most popular technology and aids in meeting every requirement except the measurement of temperature and moisture.
- The load cell and capacitive proximity transducer perform the same function as the FSR but have less evidence to support their use.
- For microclimate measurement, the dual temperature and humidity sensor is better than either of the temperature or humidity sensors alone. As noted above, it makes sense to utilise a combined temperature and humidity sensor due to the dependence of relative humidity on temperature.
- The ultrasonic and optical distance sensors do not measure any of the three quantities of interest, i.e., pressure, temperature, or moisture. However, distance sensors have been shown to improve the performance of posture classification [8]. While the ultrasonic distance sensors are used in two papers [9], [10], compared to only one [8] for the optical distance sensors, the work presented in [8] is a peer-reviewed journal article and is of higher scientific quality than [9], [10] which are conference papers.

Final Sensor Type Selection

The sensors that will be used for the prototype are:

- FSR (pressure and posture classification),
- optical distance sensors (posture classification),
- IMU (posture classification and activity monitoring), and
- dual temperature and humidity sensors (microclimate).

Table 1: Evaluation of sensor technologies against criteria 3 and 4

Author (Year)	Technology	Off the shelf	No sensor attachment to user
Ahmad (2019) [23]	Screen printed FSR	NO	YES
Cho (2019)† [9]	FSR	YES	YES
Cho (2019)† [9]	Ultrasonic distance sensor	YES	YES
Dimitrova (2019)† [1]	FSR	NO	YES
Estrada (2016)† [24]	Smart phone gyroscope	YES	NO
Feng (2020) [11]	RFID	YES	NO
Flutur (2019)† [25]	Capacitive proximity transducer	YES	YES
Fragkiadakis (2019)† [2]	FSR	YES	YES
Jeong (2021) [8]	FSR	YES	YES
Jeong (2021) [8]	Optical distance sensor	YES	YES
Kim (2019) [3]	FSR	UNKNOWN	YES
Liu (2017) [13]	Humidity sensor	YES	YES
Liu (2018) [14]	Temperature sensor	YES	YES
Liu (2019) [15]	Dual temperature and humidity sensor	YES	YES
Ma (2017) [4]	FSR	YES	YES
Ma (2017) [21]	FSR	YES	YES
Ma (2017) [21]	IMU	YES	YES
Ma (2017)† [18]	FSR	YES	YES
Ma (2017)† [18]	IMU	YES	NO
Marenzi (2013)	Capacitive sensor matrix	NO	YES
Martins (2014)† [26]	Piezoelectric gauge pressure sensors in air filled bladder	NO	YES
Meyer (2010) [27]	Capacitive textile sensor array	NO	YES
Olney (2018) [16]	Dual temperature and humidity sensor	UNKNOWN	NO
Petropoulos (2017)† [19]	IMU	UNKNOWN	NO
Postolache (2009)† [28]	BCG sensor	YES	YES
Postolache (2009)† [28]	Accelerometer	YES	YES
Qian (2018) [29]	Strain gauge	NO	NO
Ramalingam (2021)† [10]	Gyroscope	YES	NO
Ramalingam (2021)† [10]	Ultrasonic distance sensor	YES	YES
Ramalingam (2021)† [10]	Pressure sensor	UNKNOWN	YES
Roh (2018) [30]	Load cell	YES	YES
Shin (2015)† [20]	IMU	YES	NO
Tavares (2019) [12]	FBG	UNKNOWN	YES
Xu (2012)† [5]	Binary pressure sensor	UNKNOWN	YES
Xu (2013) [31]	Resistive textile sensor array	NO	YES
Yamada (2008) [6]	FSR	YES	YES
Yang (2009) [7]	FSR	YES	YES
Yang (2018) [17]	Dual temperature and humidity sensor	YES	NO
Zemp (2016) [22]	FSR	YES	YES
Zemp (2016) [22]	IMU	YES	YES

Table 2: Evaluation of sensor technologies against criteria 1, 2 and 5

Technology	Pressure	Temperature	Humidity	Sitting Posture Classification	Number of Papers**
FSR	YES	NO	NO	YES	9
Ultrasonic distance sensor	NO	NO	NO	YES	2
Capacitive proximity transducer	YES	NO	NO	YES	1
Optical distance sensor	NO	NO	NO	YES	1
Humidity sensor	NO	NO	YES	NO	1
Temperature sensor	NO	YES	NO	NO	1
Dual temperature and humidity sensor	NO	YES	YES	NO	1
IMU*	NO	NO	NO	YES	2
BCG sensor	NO	NO	NO	NO	1
Accelerometer	NO	NO	NO	NO	1
Load cell	YES	NO	NO	YES	1

* IMU in this table refers only to the use of an IMU embedded in the seat, not those uses where the IMU is attached to the user,
** Number of papers only counts those sensors that meet both criteria in Table 1.

Specific Sensors to be Purchased

- The Interlink 406 FSR is the most frequently used FSR in the literature, having been used in [4], [7], [8], [21], [22]. This sensor is available in the UK.
- The optical distance sensor used in [8] was a Sharp reflective sensor (Sharp Corporation, Osaka, Japan). Although the exact model is not given in [8], the model with the closest measuring range found in the UK is the GP2Y0A41SK0F.
- The HTU21D dual temperature and humidity sensor (TE Connectivity, Swindon, UK), used in [15], is available on a breakout board from MikroElectktronika (Belgrade, Serbia) and from the original manufacturer, TE Connectivity.
- IMU (TBD). It needs to be checked if the research group already owns appropriate IMU sensors.

Purchase List

- Square Force-Sensitive Resistor (FSR) (Interlink 406)
    - Supplier: The Pi Hut
    - Supplier Stock Number: ADA1075
    - Price: £7.25 per unit (excl. VAT), £8.70 per unit (inc. VAT)
    - Link: https://thepihut.com/products/square-force-sensitive-resistor-fsr?ref=isp_rel_prd&isp_ref_pos=3
- GP2Y0A41SK0F Sharp, Reflective Sensor
    - Supplier: RS Online
    - Supplier Stock Number: 666-6568
    - Price: £8.76 per unit (excl. VAT), £10.51 per unit (inc. VAT)
    - Link: https://uk.rs-online.com/web/p/reflective-optical-sensors/6666568
- TE Connectivity HTU21D Temperature & Humidity Sensor Add On Board Xplained Pro
    - Supplier: RS Online
    - Supplier Stock Number: 146-8217
    - Price: £19.99 per unit (excl. VAT), £23.99 per unit (inc. VAT)
    - Link: https://uk.rs-online.com/web/p/sensor-development-tools/1468217/

Costing

Of each of the components in the sensor list, it is estimated that 15 FSRs, six optical distance sensors, and eight temperature/humidity sensors will be required. The full costing of the sensor purchase, considering these quantities, is shown in Table 3.

Table 3: Costing of required components

Item	Price per unit (excl. VAT)	Price per unit (inc. VAT)	Quantity	Total Price (excl. VAT)	Total Price (inc. VAT)
Square Force-Sensitive Resistor (Interlink 406)	£7.25	£8.70	15	£108.75	£ 130.50
GP2Y0A41SK0F Sharp, Reflective Sensor	£ 8.76	£ 10.51	6	£ 52.55	£ 63.06
TE Connectivity HTU21D Temperature & Humidity Sensor Add On Board Xplained Pro	£ 19.99	£ 23.99	8	£ 159.93	£ 191.92
			Totals	**£ 321.23**	**£ 385.48**

Conclusion

Sensors used for similar applications in the literature have been assessed against five criteria. These criteria state that the sensors must:

1. be capable of measuring 1) pressure, 2) moisture, and 3) temperature at the body-seat interface,
2. be capable of being used to determine/evaluate the sitting posture of the user,
3. not require sensors to be attached to the user in any way,
4. be off the shelf components (to accelerate the hardware development), and
5. have evidence of prior successful use in the literature.

From this assessment, the following sensors have been selected for purchase:

- Interlink 406 FSR (Interlink Electronics Inc., Camarillo, California, US),
- Sharp GP2Y0A41SK0F reflective sensor (Sharp Corporation, Osaka, Japan),
- TE Connectivity HTU21D Temperature & Humidity Sensor Add on Board (TE Connectivity Ltd., Swindon, UK).

An IMU has yet to be selected, as the research group may have IMUs. Suppliers for the other sensors have been found. The total cost of all sensors is £385.48 (inc. VAT).

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Table A1: Summary of sensors used in the literature

Author (Year)	Type & Number of Sensors	Brand/Model of Sensors	Placement of Sensors	Postures Classified	Other Quantities Measured
Ahmad (2019) [23]	Screen printed FSR containing 16 sensors in a single sheet	Bespoke	16 FSR on seat base	Forward/backward/right/ left lean	None
Cho (2019)† [9]	16 FSRs; 1 or 2 ultrasonic distance sensors	FSR – unknown; ultrasonic distance sensor - HC-SR04	16 FSRs on seat base, 1 or 2 ultrasonic distance sensors on headrest	Crouching, turtle neck, bent shoulder, slouching, pelvis/spine unbalance, stress on the back, stress on the joints, crossed legs	None
Dimitrova (2019)† [1]	10 FSRs	Bespoke	4 FSRs on seat base, 6 FSRs on backrest	Healthy posture (back in contact with backrest), slouching, leaning left/right, pelvis shifted forward (this posture is also combined with slouching and left/right leaning), slouching without touching the backrest, leaning left/right without touching the backrest	None
Estrada (2016)† [24]	3 smartphones (gyroscope)	Unknown	3 smartphones placed against the spine, held in place by a bespoke vest.	Proper vs improper	None
Feng (2020) [11]	3 RFID tags and 1 RF antenna	Unknown	3 RFID tags placed on the user's spine, and 1 RF antenna placed in the backrest	Upright sitting, forward lean, backward lean, left/right hand holding face, legs crossed right over left/left over right	Respiration rate
Flutur (2019)† [25]	6 capacitive proximity transducers	Unknown	2 transducers on seat base, 4 placed on the back of the user	Unknown	None
Fragkiadakis (2019)† [2]	13 FSRs	FSR101 Shuntmode from Sensitronics	8 FSR on seat base, 4 FSR on seat back, 1 FSR on headrest	Upright sitting, forward lean, backward lean, left lean, right lean	None
Jeong (2021) [8]	6 FSRs; 6 optical distance sensors	Unsure but possibly Interlink 406 (FSR); Sharp optical distance sensor	6 FSR on seat base, 6 optical distance sensors on backrest	Leaning on seatback with back straight, not leaning on seatback back with trunk erect, flexing trunk forward about 45 degrees (slouch), leaning against an armrest with lateral bending (left/right), sitting on the leading edge with convex trunk, leaning back with hips slightly forward (slump), legs crossed (left/right), rotating the trunk about 20 degrees (left/right)	None
Kim (2019) [3]	64 FSRs	Unknown	64 FSR on seat base arranged in 8 x8 grid	Upright sitting, forward lean, backward lean, left / right lean, sitting at the front of the chair, legs crossed	None
Liu (2017) [13]	3 Humidity sensor	Honeywell HIH4000	3 sensors in seat base, each placed in a 30 mm x 40 mm by 20 mm recess cut into the seat foam	None	Moisture level at body seat interface

Table A1 (continued)

Liu (2018) [14]	64 Temperature sensor	DS18B20 Maxim Intergrated, USA	64 sensors on seat base in an 8 x 8 grid	None	Temperature at body seat interface
Liu (2019) [15]	3 Dual temperature and humidity sensor	HTU21D TE Connectivity Ltd	3 sensors in seat base, each placed in a 30 mm x 40 mm by 20 mm recess cut into the seat foam	None	Moisture level and temperature at body seat interface
Ma (2017) [4]	12 FSR	Interlink 406	7 on seat base, 5 on backrest	Upright sitting, forward lean, backward lean, left lean, right lean	None
Ma (2017) [21]	6 FSRs; 1 IMU	Interlink 406; MPU9250 is a 9-DoF IMU	6 FSR on seat base, 1 IMU in seat base (centrally placed)		Activity level (light, moderate, vigorous)
Ma (2017)† [18]	5 FSRs; 2 IMUs	Shimmer motion sensor (IMU)	5 FSR on seat base, 1 IMU on each wrist of user	Proper sitting, forward lean, backward lean, left/right lean	Activity level monitoring
Marenzi (2013)	Capacitive force sensor matrix with 100 sensing elements	Bespoke	100 capacitive force sensors arranged in a 10 x 10 grid	None	Presure distribution and center of pressure
Martins (2014)† [26]	8 Piezoelectric gauge pressure sensors inside air-filled bladders	Honeywell 24PC	4 in seat base, 4 on backrest	Upright sitting, forward lean, backward lean, left/right lean	None
Meyer (2010) [27]	capacitive Textile sensor array with 240 sensing elements	Bespoke	240 capacitive sensing elements in a single sheet placed on seat base	Upright sitting, leaning right/left/forward/back, legs crossed left over right/right over left while: seated upright/leaning back/with the knees touching/with ankle	None
Olney (2018) [16]	1 Dual temperature and humidity sensor	Unknown	1 sensor on the medial thigh	None	Moisture level and temperature at body seat interface
Petropoulos (2017)† [19]	2 IMUs	Unknown	2 IMU place on the user's spine, one on upper spine, one on lower spine	Proper vs improper	None

Table A1 (continued)

Postolache (2009)† [28]	2 ballistocardiography sensors; 1 3-axis accelerometer	EMFi sensor (EMFIT L-3030) (BCG); LIS3LV02DQ (Accelerometer)	1 primary BCG on seat base, 1 secondary BCG sensor on backrest, 1 accelerometer on seat base	None	Heart rate and respiration
Qian (2018) [29]	1 Strain gauge	Bespoke	1 strain gauge attached to the lower spine of the user	Normal, slight hunchback, severe hunchback	None
Ramalingam (2021)† [10]	Unknown number of pressure sensors, 4 ultrasonic sensors, 1 MEMS gyroscope	FSR402 (Pressure), HC-SR04 (distance), UNKNOWN (Gyro)	1 gyro on head of user, four ultrasonic distance sensors on backrest, pressure sensors UNKNOWN	Proper vs improper	None
Roh (2018) [30]	4 load cells	P0236-I42, Hanjin Data Corp., Gimpo, Korea	4 load cells in seat base (one in each corner)	Upright sitting with backrest, upright sitting without backrest, front sitting with backrest, front sitting without backrest, left/right lean	None
Shin (2015)† [20]	1 IMU	Texas Instruments Sensor Tag	1 IMU placed below the collarbone of the user	forward/backwards lean	None
Tavares (2019) [12]	6 Fibre Bragg Gratings		2 FBG on backrest (near left and right scapulas), 2 FBG on seat base (near left and right ischiatic zone), 1 FBG on each of the left and right foot rests	Normal position and a variety of pressure relief positions: small frontward lean, intermediate frontward lean, full frontward lean, without feet support, intermediate sideward lean left/right, full sideways lean left/right	Breathing Rate
Xu (2012)† [5]	64 Binary pressure sensors	Unknown	48 sensors on seat base (arranged in a 6 x 8 grid), 16 sensors on back rest (arranged in a 2 x 8 grid)	Upright sitting, leaning left front/front/right front/left/right/left back/backward/right back	None
Xu (2013) [31]	Resistive Textile sensor array with 256 sensing elements	Bespoke	16 x 16 grid of pressure sensors	Upright sitting , lean forward/backward/left/right, legs crossed left over right/right over left	None
Yamada (2008) [6]	32 FSRs	Tekskan Flexiforce A201	32 sensors arranged in an 8 x 8 grid (only half of cells contain sensors)	None	Person identification, activity recognition
Yang (2009) [7]	6 FSRs	Interlink, possibly 406	6 FSR on seat base	None	Seated time, lift off frequency, sitting symmetry

Table A1 (continued)

Yang (2018) [17]	Dual temperature and humidity sensors, possibly 4	Sensitron SH15	Sensors attached directly to skin with surgical tape	None	body seat interface temperature and humidity
Zemp (2016) [22]	20 FSRs; 1 IMU	Interlink 406 (FSR); MPU-9250 Nine-Axis, MEMS Motion-Tracking Devices, InvenSense, California, US (IMU)	1 IMU on backrest, 10 FSR on seat base, 4 FSR on backrest, 3 FSR on each armrest	rested on leg, slouching, sitting on the leading edge, and slouched down.	None

† Denotes a conference paper, all other references are peer-reviewed journal articles