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Experimental research of proximity sensors for application in mobile robotics in greenhouse environment

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Abstract. Mobile robots for greenhouse automation are not yet used commercially, but scientific research are being performed in various aspects of using robots in greenhouses. For now, plant examination for diseases and insects, spraying and watering tasks are mostly considered. In all cases, a robot should be able to orient itself globally in the environment and locally relative to the working objects e.g. plants, obstacles and other robots if a multi robot system is assumed. In greenhouses, proximity sensors are used for simple object detection and distance measurement with both metallic and non-metallic materials as well as plants. Consequently, capacitive, ultrasound and optical type sensors can be used. It is known that they are affected by varying temperature, humidity and moisture conditions. In this research, we have used a specialized microclimate chamber to perform experiments in a modeled greenhouse environment with controlled temperature, relative humidity. The controlled environmental parameters were combined to represent real world greenhouse conditions. Three types of materials were used for detection (WxHxD): 1 mm steel plate 255 x 380 mm, 1 mm ABS 245 x 330 mm plastic plate, and 118 x 180 x 60 mm plastic container with water. The environment and the type of the detectable object were used as independent variables. The examined parameters, i.e. the dependent variables of the digital type sensors, were the maximum and minimum detection limits and hysteresis. A statistical analysis was performed to find the factors which may affect the reliability of proximity sensors measurements in greenhouse environment.

Keywords: greenhouse automation, mobile robots, proximity sensors, greenhouse environment.

INTRODUCTION

Mobile robots are growing in popularity in different applications. The primary challenge for these robots is navigation in different locations. This process is usually referenced as localization. Mobile robots for greenhouse automation are not yet used commercially, but scientific research are being performed in various aspects of using robots in greenhouses. Some greenhouse prototypes were already made in 1996, where the *Aurora* mobile robot (Mandow et al., 1996) performs simple greenhouse tasks autonomously and the teleoperator acts as a supervisor taking control, if needed. In more recent studies, researchers are mainly using already available base models such as the *Fitorobot* (González et al., 2009), which have been designed to operate in greenhouses for plant inspection, spraying and other purposes.

A greenhouse can be defined as a construction of polycarbonate, fiberglass or glass design used to multiply, grow and care for plants, fruit and vegetable. The mission of a greenhouse is to create suitable growing conditions for the full life of the plants (Badgery-Parker, 1999). The environmental conditions in greenhouses are characterized by high temperature and humidity levels and are not suitable for robot operation (Van Hentena et al., 2009). Also, humidity is one of the key factors in the greenhouse climate that influences robot's proximity sensors (Sethi et al., 2013). The dynamic of temperature and humidity should also be taken into consideration as humidity and temperature change rates in greenhouses can reach more than 30 percentage points and 10ºC in two hours during sunrise and sunset (Andrade et al., 2011).

Sensors are mostly used for automatic fruit harvesting systems or robots navigation (Harper & McKerrow 2001; Li et al., 2011). For localization tasks in agricultural robotics, mostly complex systems of infrared light based sensors or hybrid sensors with e.g. laser, camera or other types of sensors are used (Mehtaa, 2008). Non-contact proximity sensors are used to measure distance or for detection of objects and are well-suited for contactless recognition of plants and/or specific parts of a plant as well as for detection of special markers positioned relative to plant, so that the robot manipulator can be precisely positioned using limit switches or metallic detection type inductive sensors. Contactless operation is essential because of the necessity to minimize potential diseases spreading between plants.

The main types of proximity sensors used in the industry are ultrasound, infrared, inductive and capacitive.

Inductive sensor (Passeraub et al., 1997; Kej´ık et al., 2004) detects metallic objects and is suitable for industrial applications. This type of sensors produces a magnetic field in the vicinity of an oscillation coil. When a conductive object gets near to the coil, the eddy current on the object induced by the magnetic field reacts with the coil to change the oscillation frequency. Although the inductive sensor is simple, sensitive and suitable for industrial applications, it is unable to detect nonmetallic objects.

Capacitive sensor (Chen & Luo, 1998; Buck & Aherin, 1991) detects metals, objects with high humidity and other types of obstacles that change dielectric permeability of the space around the active area of the sensor. The sensor measures the capacitance between two electrodes and the capacitance changes when a detectable object is approaching.

There are three types of optical sensors (Lee & Allen, 1997; Stoyanov, 2000): reflective, diffusion and interrupt. Reflective type sensor is used for detecting objects and for distance measuring. The sensor uses a light emitter to emit light of specific wavelength at a certain carrier frequency and the receiver senses the light reflected from an object. The phase shift or time of flight will show the distance between the sensor and the object.

Ultrasound sensor (Li et al., 2003) uses the same principle as the bat echolocation. There are two types of ultrasound sensors: with two probes, one emitter and one receiver and with one probe, which is the emitter and receiver the same time. It has a large detecting distance and area. The drawback of ultrasound sensors lies in fact that they are affected by secondary echoes when detecting a closed hard-surface object.

If a robot is used in a controlled domestic environment (Mitka et al., 2012), its proximity sensors will work with a suitable precision and the robot operation, including the localization task, has been well studied in such environments, but the topic of how exactly the real conditions of a greenhouse-specific microclimate affect the performance of proximity sensors has not yet been thoroughly studied.

In recent researches, in order to evaluate the ability of robot parts to resist the environmental effects of a greenhouse, the analytical hierarchy process method has been used. A comparison was made of construction materials, mechanics, contacts, electronics, and inductive, optical and ultrasonic sensors, depending on the effects of the factors: the greenhouse microclimate, plant protection solutions (various pesticides, fungicides etc.), and plant fertilizers. In further research, sensitivity to environmental factors should be evaluated for the parts and sensors of horticultural robots (Lojans & Kakitis, 2012). The abovementioned fertilizer and plant protection solutions are mostly used as sprays increasing air humidity locally around the robot and in most cases also around the sprayer and hull positioning sensors. The humidity is condensing and can hypothetically affect the reliability of various contactless positioning sensors.

This paper covers experiments with inductive, capacitive, optical, and ultrasound sensors carried out in a special microclimate chamber for greenhouse environment simulation. The aim of the research is to find out if and how temperature and relative humidity affect the performance of different types of proximity sensors when detecting various obstacles.

MATERIALS AND METHODS

The sensors used in this experimental research are summarized in Table 1 and Fig. 1.

Table 1. Experimental proximity sensors description

Model	Type	Sensor interface	Dist. (mm) Min.Nom.Max.	Hysteresis, %	Response time, ms	Manu-facturer	Ref.
170710*	ultrasound	4-20 mA	150 – 500	–	25	Festo Didactic	RS1
CR30-15DN*	capacitive	NPN	0 – 10.5	20	20	Autonics	RS2
GP2Y0D 340K	optical	NPN	320 400 480	6	8	SHARP	RS3
165342*	optical	PNP	0 – 430	–	2	Festo	RS4
177464	inductive	PNP	– 4 –	10	2	Festo Didactic	RS5
184118*	ultrasound	PNP	100 – 200	5	166	Festo Didactic	RS6

*Actual configured distances can be seen in Fig. 5.

The sensors were selected to cover long-range and short-range detection as well as the most often used contactless proximity detection mechanisms: capacitive, inductive, optical-infrared, and ultrasound. Inductive type sensors should not be affected by the specific greenhouse microclimate and were included in the study for comparison purposes.

An ultrasound sensor with analog current output referenced as RS1 was modified to operate as a bipolar junction transistor NPN type digital output using a voltage divider and transistor and adjusted to operate at a 120–130 mm distance. The other adjustable sensors were also set to operate at certain distances. The operation of all sensors in control conditions is covered in detail in the results and discussion section. In addition, PNP type sensors were also modified to operate in reverse polarity.

Two models of infrared sensors of different scopes of application and pricing were used: intended for consumer electronics (RS3) and for industrial applications (RS4).

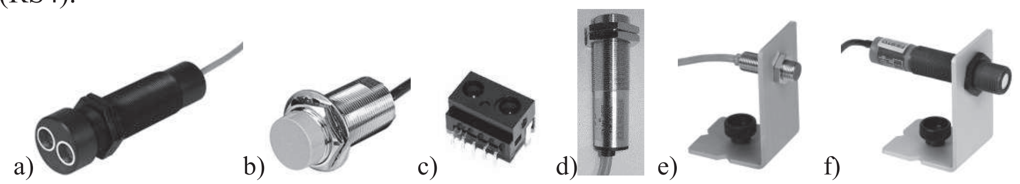

Figure 1. Experimental proximity sensors: a) – 170710; b) – CR30-15DN; c) –GP2Y0D340K; d) – 165342; e) – 177464; f) – 184118.

The performance of the selected proximity sensors was evaluated in a specialized microclimate chamber (see Fig. 2). The chamber allows to create conditions that are observed in a greenhouse during a typical daily cycle (Abdelfatah et al., 2013).

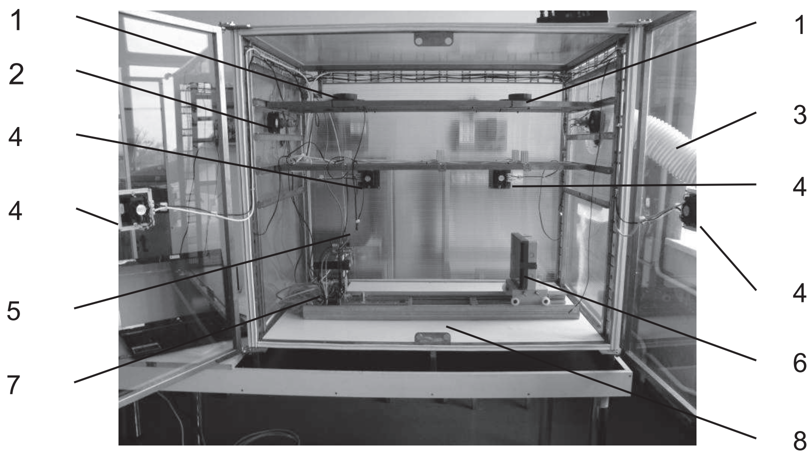

Figure 2. Microclimate chamber for simulation of greenhouse temperature and relative humidity: 1 – air recirculation fans; 2 – ventilation intake fan; 3 – ventilation outtake fan and tube; 4 – heating elements; 5 – temperature and humidity sensors; 6 – moving platform with target (container with water); 7 – senor plate; 8 – rail for target moving.

The microclimate chamber was equipped with heating and cooling elements, recirculation and ventilation fans. The controlled microclimate parameters were temperature (using a Tsic506 digital output sensor with ±0.1°C error) and relative humidity (using a Linpicco Basic A420-G 4–20 mA analog output sensor with ±3% error).

The proximity sensors were installed stationary in a test bench, but the target – the detectable object – was placed on a moving platform (see Fig. 3). The sensors were installed taking into account the manufacturer's installation instructions concerning to the minimum spacing between the sensors and so that the further edges of the hulls were the same distance away from the target. The target was moved by means of a threaded rod driven by a geared DC motor. A metric thread was used; consequently, the platform could move 1 mm per revolution of the DC motor. This step was used as the basic resolution for the platform positioning. The platform with the target was moved at a constant speed of 10 $mm \cdot s^{-1}$.

The evaluation of the sensors was performed in a number of test cycles. Each test cycle was started at the leftmost (null) position of the platform when it was at the minimum distance from the sensors (<1 mm). Then, the target was moved away until all sensors ceased target detection or up to the rightmost position (570 mm) if the environmental conditions forced at least one sensor to malfunction (i.e. it does not stop to detecting the target). Then the target was moved back to the null position.

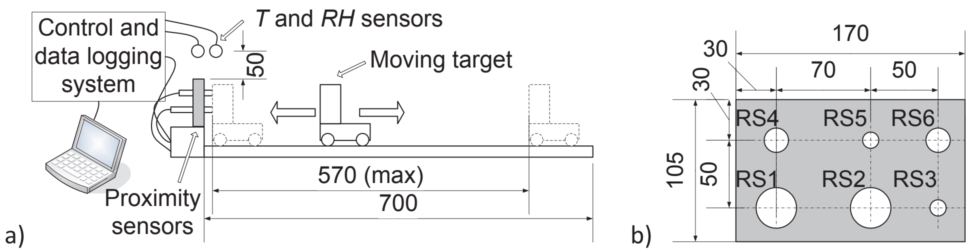

Figure 3. Sensor test bench (a) and positioning of sensors – right side view (b).

The test cycles were grouped by various environmental conditions and detectable objects. Three environmental conditions were used – control conditions, high temperature and dry air, high temperature and humid air; and three types of detectable objects: steel sheet, ABS (Acrylonitrile Butadiene Styrene) plastic sheet, and ABS plastic container with water.

The control conditions with the average temperature T = 27.8 ± 0.5°C and the relative humidity RH = 23 ± 3% were used to obtain the normal sensor detection distances for comparison. High temperature and dry air conditions were used to evaluate sensor performance in T = 24…39ºC and RH <20% and high temperature and humidity conditions in T = 24…39ºC and RH 30…100%. Temperature and relative humidity were not kept constant during the experiments (except control conditions), instead, they were increased up to their maximum values, then decreased by ventilating the microclimate chamber. This allowed to evaluate the influence of transition process on the operation of the proximity sensors. The sensors' detection limits are floating and affected by temperature and humidity. The typical profiles for both types of conditions are given in Fig. 4. The heating and ventilation process typically took approximately

40 min during which the test cycles were performed. Temperature was increased using a 1.5 kW electric heater, but humidity with a 1 kW steam generator. The water volume in the steam generator's tank was kept between 2 and 2.5 l. A steel sheet of 255 x 380 x1 mm was chosen as a detectable object to cover the situations where sensors need to detect metallic structures like greenhouse frames, racks and other robots. The steel sheet can be effectively detected by all types of proximity sensors used in the research. The ABS plastic sheet of 245 x 330 x 1 mm was used to find how sensors will operate with objects like empty plant pots, crates, plastic racks etc. The plastic sheet cannot be detected by the inductive and, due to its 1 mm thickness, also by the capacitive sensors. The 118 x 180 x 60 mm ABS plastic container composed of two parts – a non-transparent base and a transparent lid–, was filled with water and positioned to with the transparent side facing the sensors, which allowed to evaluate the infrared proximity sensor performance with various liquid containers. The capacitive sensor in turn acts with the water-filled container as a model of a vegetable or fruit (Li et al., 2012, Kviesis & Osadcuks, 2013). The water container cannot be detected with an inductive sensor.

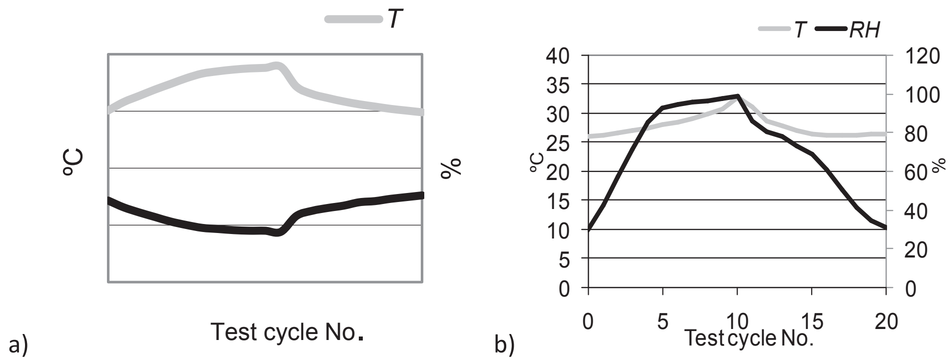

Figure 4. Typical temperature and relative humidity profiles during experiments with high temperature and low humidity conditions (a) and high temperature and high humidity (b).

Three repetitions were performed for all environmental conditions and detectable object combinations. Each repetition consisted of at least 10 test cycles for control conditions and at least 20 cycles for other conditions, thereby 546 test cycles were performed in total. The on and off state of each sensor, temperature and relative humidity were logged at each change in the target position or sensor state. Air recirculation was performed by 4 fans during all tests to ensure homogenous environmental conditions for all sensors and for the whole target moving distance.

The operation of sensors was analyzed graphically and using statistical methods: analysis of variances (ANOVA) to find whether the detectable object, various operating conditions or the operation mode (increase or decrease in T and RH) affect the switching distances of sensors; Spearman's non-parametric test was used to find whether there was a correlation between sensor operation distances and operating conditions for each type of detectable object.

RESULTS AND DISCUSSION

The typical target detection characteristics in control conditions for each sensor are given in Fig. 5. The sensing distances are the longest in the case of the consumer electronic infrared sensor RS3, but it has uncertain detection at long ranges. The industrial infrared sensor switching is more reliable, but has increased hysteresis (80 mm or 28% of maximum sensing distance).

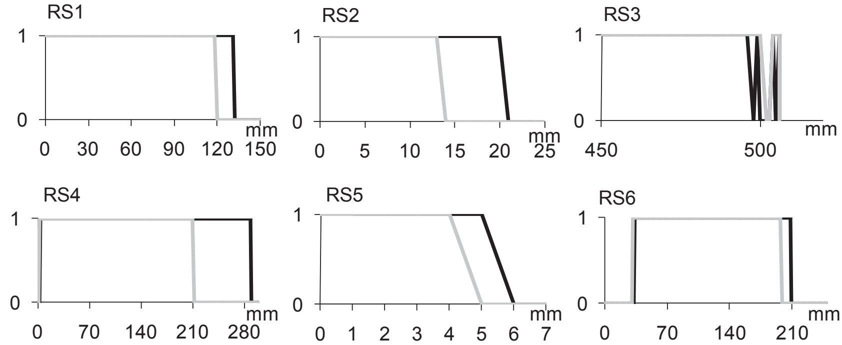

Figure 5. Typical detection distances of a 1 mm steel sheet for each type of sensor; the vertical axis shows the sensor state (1 – object detected, 0 – no detection), the black line shows the sensors' turn off point when the target is moving away, but the gray line shows the sensors' turn on point when the target is approaching: RS1 – analogous output ultrasound; RS2 – capacitive; RS3 – infrared for consumer electronics; RS4 – infrared for industrial applications; RS5 – inductive; RS6 – ultrasound with digital output.

Table 2. Average operation distances of sensors, in mm, by environmental conditions and detectable object

Sensor operation	Steel sheet			ABS sheet			ABS container with water		
	Control	High T, low RH	High T, high RH	Control	High T, low RH	High T, high RH	Control	High T, low RH	High T, high RH
RS1 off	130	127	–	128	127	–	126	124	124
RS1 on	118	120	–	120	121	–	119	119	118
RS2 off	19	15	16	–	–	–	12	12	12
RS2 on	13	13	14	–	–	–	10	10	10
RS3 off	513	460	468	460	468	485	273	265	291
RS3 on	513	459	469	459	468	485	272	265	290
RS4 off	288	304	292	312	306	315	192	191	181
RS4 on	209	227	221	235	234	239	146	144	136
RS5 off	6	7	7	–	–	–	–	–	–
RS5 on	5	6	6	–	–	–	–	–	–
RS6 off	208	207	207	207	206	203	205	204	205
RS6 on	197	199	199	199	199	196	198	197	197
RS6 min off	31	79	62	32	37	26	21	22	21
RS6 min on	34	83	63	32	41	27	23	23	24

Ultrasound sensors have moderate sensing distances and relatively small hysteresis (13 mm or 6% of the maximum sensing distance). Due to the ultrasound range sensing technology, there is a limit for the minimum sensing distance, which can be observed in the RS6 operation. This effect is not observed with the 4…20 mA analog output ultrasound sensor RS1, because of the minimum loop current and transistor switch added at the output for the experiments. The average operation distances for all test cycles in three repetitions grouped by environmental conditions and detectable objects are summarized in Table 2. The table shows both the sensor turn-off distance when the target is moving away and the turn-on distance when the target is approaching. It also shows the minimum detecting distance for the digital output ultrasound sensor RS6.

During the experiments in high temperature and humidity, the ultrasound sensor RS1 malfunctioned with the steel and plastic sheet targets. It took the form of doubling the detection distance in comparison to the tests in control conditions. Most likely, it was internal sensor failure and therefore its measurements were included in further analysis only for comparison purposes.

A statistical analysis was performed for the turn off and on distances, target detection hysteresis and the RS6 minimum detecting distance and its hysteresis. As was expected, the analysis of variances for all parameters shows that the type of detectable material significantly affects the sensor operation. The only exception is the hysteresis of RS3, because, as it was mentioned before, its operation at long distances is uncertain.

An analysis of variances was also performed to find out whether heating and ventilation transient processes have any effect on the detecting distances of sensors. The results show that for almost all of the environmental conditions and detectable objects (with the exception of the 3rd repetition for the ABS sheet in high T and RH) there is statistically significant difference ($P < 0.05$) in the turn-off distance for the ultrasound sensor RS6 and also with all conditions and objects (with the exception of 2 repetitions with steel and 1 repetition with the ABS sheet in the same environmental conditions) for the RS6 turn-on distances. Despite the statistical significance, these changes are only within 3 mm, which is 1.5% of the detection distance. Both the turn on and off distances for the ultrasound sensor are consequently higher by this value when T and RH are increasing. It was stated that the temperature and humidity transients had no effect on the hysteresis of RS6. It is also to be mentioned that the ultrasound sensor RS1, which failed in a number of tests, has also strong dependency on transients. In approximately 40% of the cases, transients also affect the switching distances of both infrared sensors, but again there are no significant differences in hysteresis.

The results of the analysis of variances (P-values) on the effect of the environmental conditions factors are summarized in Table 3. The analysis included test cycles for high T, low RH and high T and high RH conditions, i.e. it shows whether significant differences were observed in the object detection parameters between these two conditions. The results show that environmental conditions have no impact on the inductive type sensor RS5 and it was excluded from this analysis. The most significant changes in the results for all sensor parameters between the environmental conditions are for steel and ABS sheets. The only exception is for the RS3, as in the previous analysis.

The explanation could be that changing environment has effect not only on the physical phenomena used by a sensor for object detection (e.g. dielectric constant or IR ray absorption ability of air), the sensor body, the electronics it is housing, but also on the detectable object. The surrounding air heated steel and ABS sheets due to their small volume, but the temperature of the ABS container with water remained nearly constant throughout the experiments, thus the sensors that relay on the non-optical detection principle were less affected by changing environment.

Table 3. Results of the analysis of variances on the effect of environmental conditions (P-values)

Sensor operation parameter	Steel sheet	ABS sheet	ABS container with water	Sensor operation parameter	Steel sheet	ABS sheet	ABS container with water
RS1 hyst.*	0.000	0.103	0.000	RS4 hyst.	0.000	0.000	0.013
RS1 on*	0.000	0.126	0.000	RS4 on	0.000	0.000	0.000
RS1 off*	0.000	0.385	0.000	RS4 off	0.000	0.000	0.000
RS2 hyst.	0.000	–	0.155	RS6 hyst.	0.000	0.000	0.423
RS2 on	0.000	–	0.064	RS6 on	0.000	0.000	0.816
RS2 off	0.000	–	0.000	RS6 off	0.000	0.000	0.162
RS3 hyst.	0.003	0.743	0.134	RS6 min hyst.	0.020	0.000	0.215
RS3 on	0.000	0.000	0.000	RS6 min on	0.000	0.000	0.626
RS3 off	0.000	0.000	0.000	RS6 min off	0.000	0.000	0.372

* Only for comparison; – not tested

In the tests with the ABS plastic container there are, in turn, no significant differences between environmental conditions for the RS2 capacitive sensor's hysteresis and turn-on as well as for all parameters of the sensor RS6. This can be explained with moisture condensation on the detectable objects during microclimate parameters transients.

Table 4. Spearman's correlation coefficients grouped by environmental conditions and the material of detectable object

Condition	High T, high RH						High T, low RH		
Detectable object	Steel sheet		ABS sheet		ABS container with water		Steel sheet	ABS sheet	ABS container with water
Correlation with	RH	T	RH	T	RH	T	T	T	T
RS3 off	0.61	0.68	0.20	0.28	0.02	-0.39	0.16	0.29	-0.52
RS3 on	0.63	0.70	0.20	0.32	0.04	-0.37	0.18	0.30	-0.54
RS4 off	-0.86	-0.74	-0.05	0.06	-0.66	-0.87	0.08	-0.03	-0.29
RS4 on	-0.90	-0.81	-0.13	0.12	-0.69	-0.89	-0.24	-0.49	-0.23
RS6 min on	0.75	0.73	0.41	0.47	0.21	0.39	0.76	0.74	0.44
RS6 min off	0.66	0.65	0.44	0.43	0.42	0.48	0.75	0.70	0.40

Spearman's correlation coefficient was calculated to find whether there were any correlations between sensor switching parameters, temperature and relative humidity. A statistically significant $P < 0.05$ moderate to strong relationship (the absolute value of Spearman's correlation coefficient greater than 0.6) was observed for both the infrared type sensor on and off parameters in high temperature and humidity conditions and for the RS6 digital output ultrasound sensor's minimum on and off distances both in humid and dry air, but only when detecting the steel sheet. No correlation with any of the sensors hysteresis was observed. The summary of significant Spearman's correlation coefficients is given in Table 4. Note that in high T and low RH conditions, the correlations with humidity are not included as the changes in RH were no higher than 7 percentage points (see Fig. 4).

Although there is strong correlation with temperature and humidity for both infrared sensors, the coefficients are negative, i.e. while the detection distance of industrial-type sensor RS4 decreases with increase in both environmental parameters, the distance of the consumer electronics sensor RS3 increases (see Fig. 6).

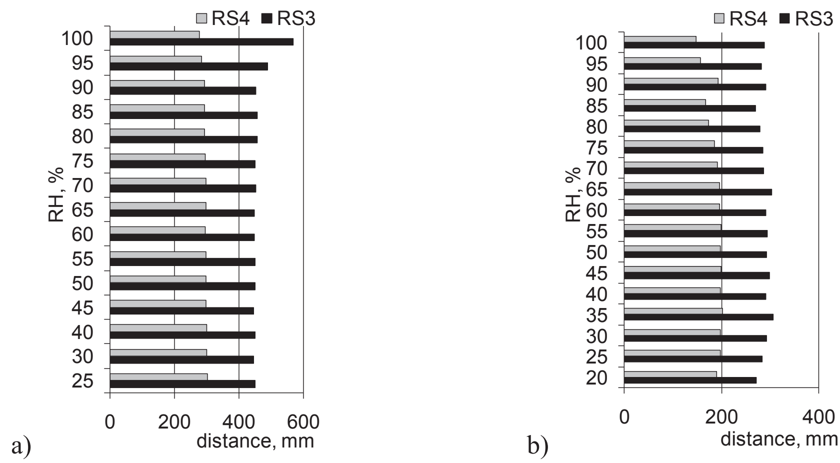

Figure 6. Switch-off distances for infrared sensors RS3 and RS4 with a steel sheet (a) and ABS plastic container filled with water (b) in high T and high RH conditions.

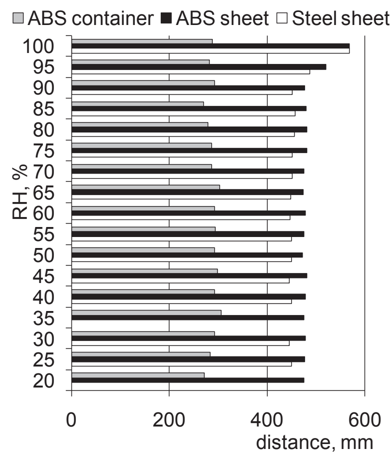

Figure 7. Switch-off distances for the infrared sensor RS3 with three types of objects in high T and high RH conditions.

It should also be pointed out that the sensor RS3 failed to detect objects at long ranges when humidity increased over 95%, as its infrared beam reflected from vapor. This reflection can be observed at a certain distance between 300 and 450 mm. This can be concluded from the fact that the RS3 sensor's detection distance for the water-filled ABS container with a transparent lid because the IR beam diffusion is smaller than for other objects and the sensor switches off properly, but with the objects that can be detected at longer ranges, the sensor does not turn off up to the maximum target distance (570 mm), which is greater than the RS3 detection distance at the control test cycles (see Fig. 7). Therefore, this type of sensors cannot be effectively used in a vaporous environment. This fact was not observed for industrial type sensor.

CONCLUSIONS

1. Infrared devices are most affected by greenhouse environment of the long-range proximity sensor types. The switching distance is strongly dependent on air relative humidity: a change in relative humidity from 30% to 100% results in a 25 mm or 8% decrease of the maximum detection distance for an industrial and a 12 mm or 3% for a consumer electronic infrared sensor. However, the infrared beam can reflect back from aerosols e.g. water vapors, and result in sensor distance detection failure.

2. Ultrasound sensors are the most reliable for long-range obstacle detection in greenhouse environment. Although statistically significant influence of environmental conditions can be observed, changes in maximum detection distances do not exceed 5 mm or 2.5% and there is no correlation with temperature and humidity. It should also be noted that there is a moderately strong correlation (Spearman's correlation coefficient > 0.7) between the minimum detection distance and temperature.

3. If the temperature of obstacles changes when heated by direct sunlight and other heat sources, it can increase the minimum detection distance of ultrasound sensors.

4. Short-range capacitive and inductive type sensors are not significantly affected by greenhouse environment, however, the obstacle detection range of a capacitive can decrease if moisture condensing occurs during temperature and humidity transients.

5. The changes in sensor detection distances should be taken into consideration when designing positioning control systems for a robot and its working units (sprayers, inspection probes, manipulators etc.).

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