PackSens: A Condition and Transport Monitoring System Based on an Embedded Sensor Platform

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Abstract. As a consequence of the growing globalization, transports which need a safe handling are increasing. Therefore, this paper introduces an innovative transport and condition monitoring system based on a mobile embedded sensor platform. The platform is equipped with a variety of sensors needed to extensively monitor a transport and can be attached directly to the transported good. The included microcontroller processes all relevant data served by the sensors in a very power efficient manner. Furthermore, it provides possible violations of previously given thresholds through a standardized Near Field Communication (NFC) interface to the user. Since falls are one major cause of damages while transportation, the presented system is the first one that not only detects every fall but also analyses the fall height and other parameters related to the fall event in real-time on the platform. The whole system was tested in different experiments where all critical situations and in particular all fall situations have been detected correctly.

Keywords: Embedded system · Condition monitoring · Transport monitoring · Low power · Sensor platform

1 Introduction

Due to the growing globalization especially in the last 20 years the local and international markets have moved close together. It is for example common today that one product is produced at different sites and that all necessary components for a particular product arrive for the final assembly "just-in-time". One aspect this example and many others have in common, is that more and more goods need to be transported from one place to another which has caused a big rise in goods traffic in recent years. For example, only the German courier-, express- and parcel-services have seen a rise of 74% in the transport volume since 2000 [1].

With the rise in goods traffic also the transports of goods with special needs like fresh or fragile products increased. For these products an incorrect transport or incorrect transport conditions like too warm or too rough environments could

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lead to big damages and (financial) problems. To overcome these issues it is quite common (at least for almost all industrial facilities) that goods are extensively checked directly after receiving them. Unfortunately, such a check is often not possible if one receives a private parcel since it could not be opened directly. And even if a damage has been detected during the incoming check it is often not possible to identify the initiator.

Modern embedded systems could provide a perfect solution for the above mentioned problems. Through the combination of a microcontroller with small Micro-Electro-Mechanical-System-sensors (MEMS-sensors) it is possible to create compact, mobile and universal sensor platforms. These platforms could be transported directly with the good to monitor the transport conditions in real-time. If a violation like an interruption of the cooling chain or a drop is detected, it is stored on the platform and the receiver is able to read out the event in less than a second during the incoming check. Obviously, this saves time and resources in industrial facilities and also enables reliable checks for private persons directly at the door. An additional advantage is that the exact time at which a violation occurred could be stored. Together with the tracking information this provides relevant information about the initiator of a possible damage. This paper introduces such an intelligent platform and highlights all components needed to build up the entire transport and condition monitoring system called *PackSens*.

The remainder of the paper is structured as follows: In Sect. 2 existing condition monitoring systems are introduced before a general overview of the *PackSens* system is given. Section 3 deals with the hardware used for the sensor platform, while the corresponding low-power concept is described in Sect. 4. In Sect. 5 the innovative fall detection and analysis algorithms are explained. The results of different experiments for the evaluation of the entire system are shown in Sect. 6. Section 7 concludes the work and gives some hints for future research.

2 Existing Systems and System Overview

Only one transport monitoring system developed by the MIT has been proposed in the scientific field yet [2]. The sensor platform of this system consists of a microcontroller, a 2.4 GHz wireless module and different analog sensors like a shock sensor, a light sensor, and a temperature sensor. With special wake-up mechanisms the platform consumes little energy but due to the simple analog sensors nearly no precise measurements are possible. Another drawback is the need for a special configuration and read-out device which increases the application costs. In the commercial field a few transport monitoring systems are available specialized for big shipment boxes like sea containers. There are the *EDR-3C* and the *Shock Timer Plus 3Dv2* from *Instrumented Sensor Technology* [3] and the *Container Security Tag ST-675* from *Savi Technology* [4], to mention only a few. All systems can monitor a variety of parameters and are very robust. But they are also huge, heavy, and expensive which makes them unsuitable for the use in smaller and in particular private transportation. A system which provides similar features but is small enough that it could be used in smaller transportation scenarios is the *SenseAware* from *FedEx* [5]. However, this system is apparently only available to companies. There are, to our best knowledge, only two systems which are potentially also designed for the demands of the private sector, namely *DropTag* from *Cambridge Consultants* [6] and *Pakkcheck* [7]. But both systems are not yet available on the market and their final functionality still remains unclear. Finally, there are also several systems that are specialized in the monitoring of just one certain parameter like temperature [8] or shock [9].

Our novel *PackSens* system combines all advantages of the above mentioned systems and adds some new functions which no other system yet provides: It is very small and lightweight however robust so that it could be used in both, private transportation and big industrial containers for instance. The platform also implements a sophisticated low-power concept to enable a long autonomous operating time. Since not all components are needed in every use case, the entire platform is build in a modular way. Components could be turned off or omitted also physically with no effect on the remaining functions. Another novel feature is the on-board detection and analysis of drop events. Even if drop events are a major cause for damages while transportation, it seems that no system yet performs a deeper detection and analysis. The standardized communication module which is based on NFC is also an innovative feature as it enables the configuration and read-out through a standard NFC-capable smartphone or computer without any complex linking.

Figure 1 sketches the entire *PackSens* system. The main part is the sensor platform itself which will be transported with the good that should be monitored. The heart is a microcontroller which connects all components, in particular all "monitoring" sensors. To provide a non-volatile storage of critical events together with precise timestamps a flash memory and a real-time clock module are included. The power supply is realized with the help of a single-cell Lithium-Polymer-battery. The size and capacity of this battery could be chosen arbitrarily and by this adjusted to different needs. The power supply also includes a charging circuit for the battery which uses the upcoming QI-standard to provide external charging power to the platform without the need for any cable connection. For the communication with the configuration and read-out

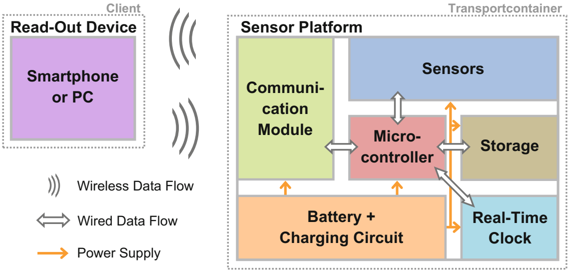

Fig. 1. Overview of the entire *PackSens* transport and condition monitoring system.

device a NFC-based interface is included. This allows a quick and easy to link communication even through a completely closed transport box. Moreover, any NFC-capable smartphone or PC equipped with an appropriate app can be used as a configuration and read-out device.

3 Hardware

The *PackSens* sensor platform is equipped with a variety of sensors which allow the precise monitoring of all important parameters while the transportation of a good. As already mentioned before, the occurrence of a drop is one very important parameter, which is also closely related to shocks (=high accelerations) and vibrations. All three parameters are monitored with the help of two accelerometers, one providing a high resolution for lower accelerations (low-g accelerometer *ST - LIS3DH*) and one offering a high measuring range (high-g accelerometer *ST - H3LIS200DL*). Other important parameters, at least for some transportation goods, are temperature, humidity and pressure. As a consequence the sensor platform includes a *NXP - PCT2075* temperature sensor, a *ST - HTS221* humidity sensor and a *ST - LPS25HB* pressure sensor. Additionally, an ambient light sensor (*LiteOn - LTR-303ALS-01*) is included that serves for two purposes: On the one hand it could be used to detect high light intensities on light sensitive goods, on the other hand it could be used to detect unauthorized openings of a transport container.

All chosen sensors not only had to be as cheap, as small, and as power-saving as possible but they also had to provide a digital output and if possible a threshold interrupt output that is fired if the measured value goes above or below a given threshold. These requirements help to reduce the demands for the microcontroller and are a key part of our low-power concept. Another mandatory requirement all sensors had to fulfil are low-power modes in which the sensor is turned off and consumes almost no energy. This is also helpful to decrease the power consumption through the deactivation of sensors which are currently not needed.

All components discussed so far together with the passive NFC- and QI-interface are connected to a *SAMD20G15* microcontroller from *Atmel*. This Cortex-M0+ controller is cheap but provides enough computational power and memory for all tasks that have to be performed on the platform. It also provides interrupts on nearly all I/O-pins and offers a deep sleep mode in which almost no energy is consumed. To integrate all components in a robust and compact manner a PCB was developed and enclosed with a custom-made case (see Fig. 2). The final sensor platform is smaller than a credit card and with a weight of about 50 g it can be add to any transport box without increasing the weight significantly.

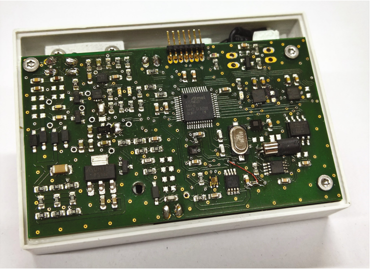

Fig. 2. The *PackSens* sensor platform. PCB dimensions: 68 mm × 41 mm. Outer case dimensions: 71 mm × 50 mm × 19 mm. Weight of the whole platform: 52 g.

4 Low-Power Concept

Since the costs and the size of the battery, the run-time and many other important parameters of the condition monitoring system are influenced by the power consumption, a special effort has been put in its reduction. While it would be the easiest way to just choose the cheapest sensor for each parameter and then always monitor the corresponding output with the microcontroller, this concept is very energy consuming. Besides other issues, the biggest problem with this straightforward concept is the continuous monitoring which must be performed by the microcontroller. To achieve this the controller always has to be in its normal operation mode in which it consumes quite a lot of energy (in case of the *Atmel SAMD20* about 3.1 mA). A big energy saving can be achieved by reducing the time the microcontroller is in this power consuming operation mode. So the monitoring is sourced out to the sensors and the microcontroller is put into a deep sleep mode most of the time where it consumes almost no energy (in case of the *Atmel SAMD20* about 4 µA). Fortunately, many modern sensors support this outsourcing through a threshold monitoring directly on the sensor's IC. If the current output of such a sensor is above or below a previous given threshold the IC provides an interrupt. This interrupt is used to wake up the microcontroller from its sleep. The controller then checks, computes, and stores a possible violation before it is put in the deep sleep mode again. With this interrupt-driven concept the microcontroller is only activated in case of a possible important event which saves a lot of energy. The concept is also illustrated in Fig. 3 and it underlines the special requirements for the component selection as discussed in the previous section.

Another problem in terms of energy consumption are critical events that last for a longer time. These events would trigger the threshold interrupt and by this wake up the microcontroller every time a measurement is taken. To overcome this issue the threshold interrupts are changed after the first violation of a threshold in such a manner that if a sensor output has triggered an upper threshold the next interrupt is only triggered if the output is again below this threshold and vice versa.

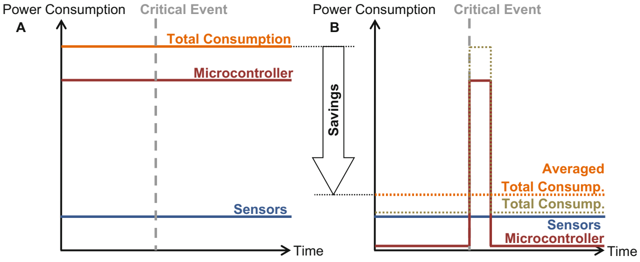

Fig. 3. Schematic comparison of the energy consumption with the straightforward concept (A) and the interrupt-driven concept (B). The real power consumption values of the *PackSens* highly depend on the configuration (see Sect. 6).

5 Fall Detection

Falls are a major cause of problems and damages while transportation. Therefore, a special fall detection was developed which not only detects falls but also tries to analyze different fall parameters. As already introduced, accelerometers are used to detect falls which is done through a characteristic pattern of the resulting acceleration. Such an ideal pattern is shown as the red line in Fig. 4. It could be divided into four parts: In the pre-fall phase before the start of the fall the normal acceleration of 1 g due to gravity acts on the good. Then after the fall start the good is in free fall and no acceleration is measurable. It becomes faster until it hits the ground or something similar. This is called the impact. Here, a very high acceleration is detected since the good is stopped immediately and the kinetic energy gained in the free-fall phase is converted. After the fall, in the post-fall phase, again the normal acceleration due to gravity acts on the good while it lays on the ground. Especially through the characteristic and large peak in the impact phase this pattern could be easily spotted. Unfortunately, an acceleration measurement during a real drop like it is shown as the dots in

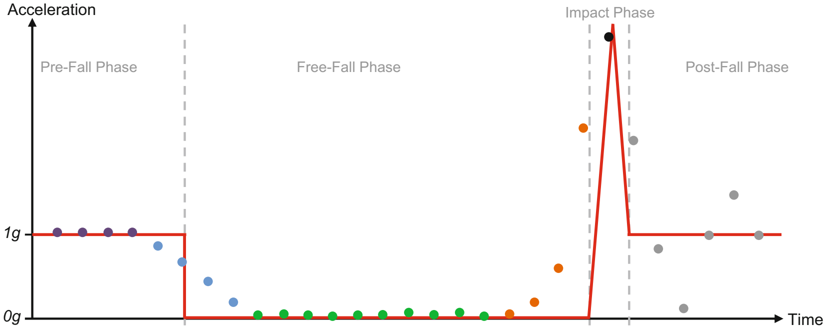

Fig. 4. Red line: ideal acceleration on an object during a fall. Dots: schematic representation of the measured acceleration during a real fall. (Color figure online)

Fig. 4 does not provide such a perfect pattern. In particular the transitions from one phase to another cannot be clearly spotted anymore and the post-fall phase is not as smooth and steady as in the ideal case because of rebounds from the impact surface. The fluctuations also vary with every measurement.

For the pure detection of a fall the literature provides in general three different concepts: pattern recognition [10], subsequence matching [11] and the threshold concept ([10,12]). While the first two methods are unsuitable for the presented system due to the required training set and the required computational power, the threshold concept suits very good and is the base for the algorithm in this work. In this concept the acceleration measurement has to cross one or more different thresholds which characterize the fall pattern before a drop is detected. To fit to the low-power concept the detection of the first threshold is outsourced to the low-g accelerometer. It provides an interrupt as soon as the acceleration on all three axis is below 0.375 g for at least ten samples which corresponds to a free fall of 10 ms and is a good first hint for a fall. After this trigger every sample is analyzed in real-time and it is checked whether its magnitude is above a value of 9.6 g. In this case it corresponds to the impact peak and a fall is detected that has to be analyzed. If the value is not reached no fall happened or the fall had a very soft impact. The thresholds used for the detection as well as all following thresholds were chosen empirically.

In the following analysis the fall height is determined first. For its calculation two methods are known in general: The impact-based method [13] uses the impact measurements and different specific information about the drop for the height calculation. Some of the required information, in particular about the impact surface, are not accessible by the presented system which is the main reason why the second method based on the free-fall time [14] is used for the analysis. To gain the free-fall time, the measured samples which belong to the free-fall phase had to be determined in a first step. While a coarse estimation of the amount of these samples and the corresponding fall height is simple and has been done already in some works (e.g. in [14]), this is not sufficient for the proposed system. Since the outcome of the system should serve as a proof in case of damages, it has to be very precise and especially respect the mentioned imperfections appearing in a real fall measurement. This is the reason why a more sophisticated algorithm was developed to find the samples in the free-fall phase and why the system not only outputs one fall height, but a lower and an upper bound. For the lower bound only the samples are taken into account which are part of the free-fall phase with absolute certainty (in Fig. 4 these samples are marked in green). For the upper bound all samples starting from the last one in the pre-fall phase (last violet dot in Fig. 4) until the peak sample (black dot in Fig. 4) are considered. With the number of samples for each bound and the sampling rate, the free-fall times are calculated. Since the good was accelerated with the known acceleration due to gravity g between these times (t) a lower and higher bound for the fall height h could be calculated with Eq. 1.

$$h = \frac{1}{2} \cdot g \cdot t^2 \tag{1}$$

There are many special cases that can occur during a fall which could falsify the fall height or which are interesting for the user. Examples are that the good could be thrown or that the good could fall down some stairs which leads to many successive impacts. Since it is impossible to detect all possible special cases directly on the platform, the main focus is on detecting each and every fall independent of a potential special case. After that the fall height is estimated as described above and all known special cases are checked with different methods. In the current version potential throws, the occurrence of a second impact and the occurrence of an intermediate peak in the free-fall phase are detected. Of particular interest is a throw upwards since in this special case the free-fall phase is detected from leaving the hand until the impact and so the calculated fall height would be estimated far too high. Since the detection methods are not completely safe, the outcome is given to the user only as a hint and all raw acceleration data of every fall is additionally stored and also made accessible to the user. So the user can, in case of a damage, follow the hints and perform a detailed analysis afterwards.

Another parameter that is analysed after a fall is the impact strength. This is an interesting information because it could be for example possible that a good is thrown or dropped on purpose which is no problem if it is caught afterwards. The caught then equals a soft landing with a low impact strength. One simple way to gain the impact strength is an analysis of the height of the acceleration peak in the impact phase. However, since this peak normally exceeds the measuring range of standard accelerometers, we came up with a new and different way for the evaluation: By looking at the dominating frequencies in the post-fall phase a good estimation can be made on the impact strength. If the dominating frequencies are low the good has landed on a probably soft and elastic surface. If the dominating frequencies are high the impact surface is probably hard and inelastic. Thus, for the detection of the impact strength at least 64 samples after the peak of the fall are additionally stored and fed into a frequency analysis routine where frequencies around 1.5 Hz and 3 Hz are analyzed. The result of this analysis directly corresponds to the impact strength.

6 Experiments and Results

6.1 Fall Detection

Since it is an important but complex part of the system the fall detection and analysis was tested first. Therefor the sensor platform was fixed in different transport boxes out of cardboard and then dropped from different heights with the help of a drop tester. The first box was a small one (outer dimensions: 19 cm × 18.5 cm × 13 cm) made out of thin 1-layer cardboard with a total weight of about 145 g, the second one was a bigger box (outer dimensions: 31 cm × 23.5 cm × 12 cm) made out of thick 1-layer cardboard with a total weight of about 500 g. During the tests different special cases were simulated and their detection was checked, too. In total 90 test falls with fall heights between 0.3 m and 1.5 m were performed and the results are summarized in Table 1. As one can

Table 1. Test results for the fall detection and analysis.

	True positives	False positives	False negatives
Fall detection	100% (90)	0% (0)	
Fall height	91.1% (82)	8.9% (8)	
Impact strength	82.1% (64)	17.9% (14)	
Second impact	58% (7)	2.2% (2)	42% (5)
Throw	100% (12)	0% (0)	0% (0)

see the main goal of detecting each and every fall was achieved. Moreover, the fall height detection provides very good results. The only cases where the lower bound of the fall height was wrong are the special cases with a throw upwards. But since the throw detection worked in every tested case these false results could be filtered out effectively. For the check of the impact strength detection every fall, except the 12 which had a second impact, was categorized as a fall with a soft or a hard landing. Afterwards, it was checked whether the frequency analysis provides the same result. While this achieved quite good results the detection of the second impact had some issues. Only about one half of the falls with a second impact were detected correctly and also about 2% of all tested falls were incorrectly classified as falls with a second impact. As a consequence the impact strength detection as well as the second impact detection still need some improvement but they already provide a good hint for the user, exactly as intended.

6.2 Energy Consumption

Since the energy consumption is a critical parameter of the sensor platform it was also tested extensively. The results are shown in Table 2. Here, the measured power consumption is shown for every component on the sensor platform in two different configurations. For the ground consumption the component is configured to be active but all parameters are set in such a way that the minimal power is consumed. This means in case of a sensor that for example the resolution and the measuring rate are set to the minimal possible value. In the worst-case configuration every parameter of the certain component is configured in such a way that it consumes the maximum power. The most interesting results are the total power consumptions of the sensor platform in the last row. If the platform is activated the ground consumption adds up to about 17 µA which is mainly characterized by the flash storage, the real-time clock and the "sleeping" microcontroller and corresponds to an uptime of about 1.2 years using a small 180 mAh battery. Depending on the settings of the user the power consumption of the activated sensors additionally adds up to the platforms ground consumption. The total consumption in the active mode is between 17 µA and 2 mA depending on the number of activated sensors and their settings. In case of a threshold violation the consumption is shortly increased by about 3.1 mA

Table 2. Energy consumption of the different components of the *PackSens* sensor platform. Measuring conditions: about 23 °C, about 400 LUX.

Component	Ground consumption	Worst-case consumption
Flash storage	11.1 µA	11.1 µA
Real-time clock	0.7 µA	0.7 µA
Temperature sensor	about 98.5 µA	about 109.5 µA
Light sensor	400 µA	535.5 µA
Pressure sensor	about 6 µA	705 µA
Accelerometer - low G	21 µA	21 µA
Accelerometer - high G	about 25 µA	401 µA
Humidity sensor	10 µA	218 µA
Microcontroller	about 4 µA (sleep)	3.1 mA (active)
Sensor platform (in sleep mode)	about 17 µA	2 mA (everything monitored)

through the active consumption of the microcontroller. But since this is normally only the case for a very short amount of time (compared to the whole running time), the overall power consumption does not really change. This leads to an uptime of around 3.75 days with a small 180 mAh battery if all sensors are active and configured with the worst-case configuration. For a rather typical configuration like it is used in the next section (see Table 3 for the configuration details) the sensor platform draws about 770 µA which leads to an uptime of around 9.7 days with the same battery. Even if the calculated runtimes should be enough for every normal transport the uptime can always be easily increased by using a larger battery.

6.3 Condition Monitoring System

To finally evaluate the entire condition monitoring system, different transport scenarios had been tested in the laboratory. This kind of tests had been preferred to actual shipments since the real conditions and violations would have been completely unknown and an evaluation of the system would not be possible. In all tests the system was used exactly as a user would do it. The platform was fixed inside a transport box out of cardboard, configured through a specially developed Android app from outside and while the incoming check the data was read out again with the app. During the tests, different likely scenarios like a normal transport with falls and an opening or a transport with critical temperature and humidity phases (here the platform was used without a box) had been simulated. Exemplary, the outcome of the normal transport scenario is shown in Table 3. On the left hand side one can see the tested events and on the right hand side the output of the system is shown. Each event was detected immediately and all shown events are exactly as expected. It is remarkable that often two shock events for the same acceleration peak were detected. The reason

Table 3. Results for the tests of a normal transport with falls and an opening event. Active parameters: Fall, light (upper/lower threshold: 100 LUX/20 LUX, sampling rate: 2 s), shock (threshold: 15.625 g, sampling rate: 400 Hz).

Test		System output	
Time	Action	Time	Event
19:40	Fall, about 1 m, caught	19:40	Fall event: 0.47 m - ?[a], Soft landing
		19:40	Shock event: x: 21.9 g
19:41	Opening	19:41	Light event: 129 LUX
19:42	Closing	19:42	Light event: 0 LUX
19:43	Hit against box	19:43	Shock event: y: -89 g
19:44	Throw upwards	19:44	2x Shock event: y: -43.8 g, z: -15.6 g
		19:44	Fall event: 2.33 m–2.98 m, Soft landing, Throw
19:45	Fall, about 1 m	19:45	Fall event: 0.94 m - ?[a], Hard landing
		19:45	2x Shock event: y: -15.6 g, y: -20.3 g

[a] If the transition between the pre-fall and the free-fall phase is very unclear the system does not output an upper bound for the height.

for this is the high sampling rate of the high-g accelerometer which leads to a double detection of large peaks[1] or to a detection of the rebouncing after a fall. Also in the other tests all events were detected and the outcome was as expected. However, in the test results of different critical temperatures and humidities a delayed event detection was observed. While a certain delay is normal for these parameters these delays could probably be nevertheless reduced by an improved positioning of the sensors within the custom-made case (see Fig. 2).

7 Conclusion

In this paper we introduced an innovative transport monitoring system called *PackSens*. The system consists of a mobile embedded sensor platform and a configuration and read-out device. While the configuration and read-out device could be any NFC-enabled smartphone or PC with a custom-made software, the sensor platform is a highly specialized design. It uses a variety of carefully selected sensors to monitor violations of given thresholds for all relevant parameters during transportation. To guarantee a long run-time a highly adapted low-power concept was implemented, which outsources the threshold monitoring to the sensors and exploits the sleep modes of the microcontroller. Tests showed that even with a small battery run-times between 4 days and about 1.2 years are possible. A unique feature of the *PackSens* system is a newly developed fall detection and

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[1] In the case of the shock detection the method described in Sect. 4 for detecting only the start and end of a critical event is not used since shock events are by nature always very short.

analysis. With the help of different successive thresholds every fall of a monitored good is detected and the fall height is estimated. Through methods like a special frequency analysis also the impact strength and other parameters of the fall are analyzed. While the fall detection and the fall height estimation showed very good results, the detection of additional fall parameters and in particular the detection of certain special cases still need some improvement. Also the position of the temperature and humidity sensor should be optimized. Nevertheless, the *PackSens* system is already an effective transport and condition monitoring system which could provide huge advantages in the area of transports and logistics.

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