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Measurement and estimation of surface resistance on ESD-protected workstations

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***Abstract* – The prevention of electrostatic discharge (ESD) is an absolute must in the electronics industry, and surfaces of workstations have to be of specific resistance for effective ESD protection. The R&D project presented in the paper investigates the—so far rarely researched—dependence of worksurface resistance on ambient conditions and surface contamination. Upon examination of known and assumed dependencies, measurement and instrumentation are outlined, relying on existing automated facility management, autonomous devices, and manual measurement/logging. Further parts of the paper report on an ongoing analysis of the data being obtained, as well as their use in building models of surface resistance that can be applied in optimizing work and maintenance processes in the electronics industry.**

Keywords— Manufacturing, ESD protection, surface resistance, modeling

I. INTRODUCTION

Research and development of the past 1–2 decades brought forth data processing and model building tools able to tackle the complex interdependencies of large production systems at multiple levels of organizational and functional hierarchy, as well as sophisticated methods and technologies for prediction, planning and control of industrial processes. Several of these have ripened from experimental pilot to industrial application, and find growing acceptance in production environments that are otherwise pressed by tightening environmental and health regulations, and by increasing competition that requires costs to be cut while maintaining or improving product quality, flexibility and responsiveness. An important development contributing to these trends is the increase of process transparency by means of massive unique identification, process/product data and measured quantities, allowing better models to be built and utilized, possibly also yielding a more accurate picture of the borders of safe operating conditions. The latter can, in turn, be approached more closely, resulting in savings and improved quality and process safety guarantees.

The specific case examined in the paper is that of the electronics industry where products must be protected from *electrostatic discharge (ESD)*, especially at stages of production, maintenance, or repair where no protective shielding of the product is present. ESD occurs when electrostatic charges accumulate in production equipment, clothing of personnel, etc., and are discharged in an *ESD event*. Discharge passing through semiconductor components may inflict irreparable damage which can remain hidden long enough for a damaged device to slip through immediate quality checks—such risks must, therefore, be removed from the processes of production and handling. This consists in ensuring that (1) electrostatic charges accumulate as little as possible in the environment, equipment, and personnel, and (2) if a discharge event does occur after all, discharge current must be limited to protect sensitive components from overcurrent. In industrial practice, this is ensured by (1) the use of conductive materials for floors, clothing, worksurfaces (Figure 1) and certain tools, as well as protective ground connections at specific points of production equipment, and by (2) the surface resistivity of materials in possible physical contact with the semiconductor components being within a range that allows draining of accumulated electrostatic charge but keeps discharge current within safe limits [15, 8].

The transfer resistance of surfaces depends on several environmental conditions as well as deposits on the surface—in present-day practice, neither precise and frequent measurement of the contributing conditions, nor a minimal-impact (optimally, contact-free) acquisition of actual resistance values are part of industrial practice. Therefore, *an accurate model of the dependence of surface resistance on ambient conditions and process parameters is not relied on in present-day industrial practice, implying relatively rough estimations and wide safety margins that are maintained at high costs*. It is expected that more accu-

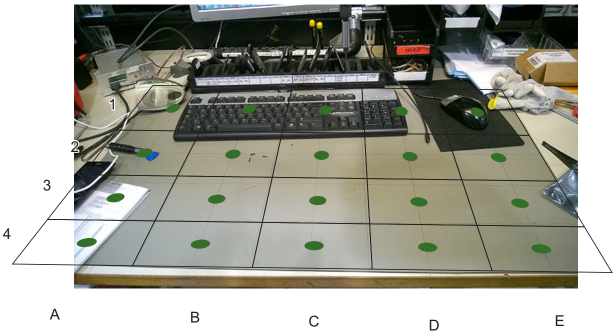

Fig. 1. Example of an ESD-protected worksurface with green marks showing the locations of resistance measurement carried out in this research

rate knowledge of a surface resistance model will eventually contribute to improved efficiency in maintaining safe operating conditions.

The paper presents a measurement instrumentation and data preprocessing setup in the context of an R&D project that has *collected measurement data of ambient conditions and work activity logs assumed to be relevant for modeling the surface resistance of worksurfaces of manually operated ESD-protected workstations*. In further parts, the paper is structured as follows. After an overview of preliminaries (Section II.), the extent and methods of measurement are presented (Section III.), followed by first findings of raw data (Section IV.), and the concept of data preparation, model building, and results of modeling itself (Section V.). Section VI. recapitulates the novelties achieved by the research so far, and highlights further possibilities of measurement and online diagnostics.

II. PREVIOUS WORK

A. *ESD protection in literature*

The mainstream of ESD-related literature deals, in fact, not directly with ESD protection but with the nature and effects of ESD events, i.e., assumes that discharge does already occur [4, 9]. A major share is taken by models (i.e., substituting circuits) of equipment or personnel potentially carrying accumulated charge [7, 6], facilitating comparative characterization [4], formal analysis, simulation of ESD events [9], and definition of robustness requirements for semiconductor components and their protective circuits. The second major group of works deals with robustness of semiconductors, devices and protective circuits against electrostatic discharge [11, 13, 19]. Also here, the occurrence of an ESD event is assumed, while research presented here is aimed at ensuring their continuous prevention—hence, little of these two major problem areas are directly related to our focal problem.

B. *Relevant conditions in other domains*

Earlier experience has already revealed that dust settling on the worksurface, in combination with humidity and temperature of ambient air, has impact on the resistance of ESD-protected worksurfaces. Therefore, it is worth examining how these conditions are represented in literature in other domains [17, 16]. Relevant in this context are results regarding particulate matter, aerosols and settling of dust [21, 10, 12] which reveal much regarding expected fluctuations of dust density, even though care must be taken regarding the specific composition and ratio of mineral particles, cellulose and skin fragments which differ in outdoor environments and closed airspaces of manufacturing facilities. While some sources deal with the mechanical behavior and handling of dust (e.g., accumulation and removal from photovoltaic panels [14]), research has also been extended to its transmittance/reflectance, especially in the infrared spectrum. A number of sources point out that moisture captured by settled dust exhibits definite spectral patterns [3] which are potentially useful in estimating surface resistance properties as well—the more so as *this would allow online contactless measurement with minimal impact on ongoing work processes*.

C. *Industrial experience*

Empirical experience has revealed over the decades that ambient temperature, humidity and deposits on the surface have impact on the resistance of ESD-protected worksurfaces—nonetheless, it must be noted that these are much influenced by production practice, such as cleaning, choice of materials in tools and clothing, and artificial control of ambient conditions. The Ishikawa diagram shown in Figure 2 reflects the relevance of contributing factors recognized in today's production practice. Note that the relevance predicates shown reflect the impact of factors under *nominal operating conditions* which are kept in safe distance from potential risk zones by a wide margin that precludes hazards even with little opportunity of measurement and intervention. Regarding relative humidity, a 30% limit is seen as a rule of thumb: below this value the resistance of rubber, and most polymer, surfaces may rise beyond safe limits, necessitating very costly humidity control, e.g., in cold and dry outdoor weather [2, 18, 1].

III. MEASUREMENT SETUP: CONCEPT AND EXTENT

A. *Purpose of measurement*

As outlined before, the purpose of measurements presented here is to gain more accurate knowledge of the dependence of the surface resistance of ESD-protected worksurfaces on selected ambient conditions (temperature, relative humidity, floating/settled dust, regular work-related activities and cleaning/maintenance measures). The quantities of interest are shown in an Ishikawa diagram revised

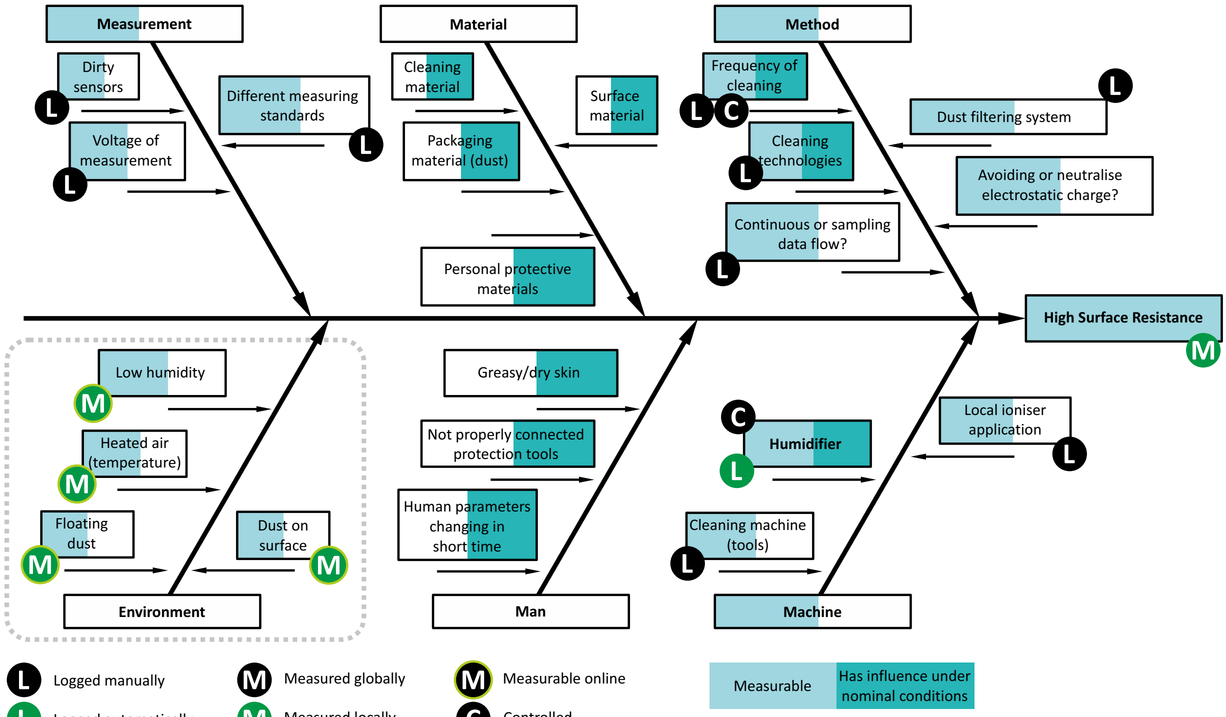

Fig. 2. Revised diagram of dependencies and controllable/measurable quantities—note the shift of focus towards previously marginal factors (see circled are at the bottom left of the fishbone diagram)

in the course of our research (Figure 2). The figure shows a shift of attention towards quantities that had less impact under close-to-nominal operating conditions (see the framed area at the bottom left of the diagram).

B. Measurement and instrumentation

Data gathered during research had three sources: (1) downloads from automated facility management records covering outdoor and indoor facility-level temperature and relative humidity with 650–700 datasets of 8 scalar values weekly (sampling every 15 minutes), (2) indoor temperature, wet-bulb temperature, relative humidity, and floating dust concentration in the vicinity of a selected workstation, measured by independent logging devices delivering data via periodic manual downloads, yielding 1900–2100×3 scalars a week for temperature, wet-bulb and relative humidity, and 3800–4000 scalars a week for floating dust density, and (3) manually logged cleaning event dates (1–5 times a week), and manually measured resistance values taken once a week on 20 discrete grid points of the worksurface of the selected workstation (Figure 1). Logging devices were designed and procured in-house, and contain a set of sensors, an independently running real-time clock (RTC), and a microcontroller for immediate conversion, time-stamped storage (EEPROM) and communication of measurements through a periodically connected serial interface (see Figure 4). Logging devices have their own independent power source. Relative humidity, wet-bulb and ambient temperature measurements relied on off-the-shelf semiconductor components, and floating dust density was likewise measured using a commercial optical sensor. Surface resistance measurements were carried out between a common ground point and the worksurface, using a probe of standard weight and geometry for the latter [5].

Clearly, the selection of measured quantities, and the degree of measurement automation leaves much reserve to be exploited for successful roll-out in everyday production—measuring the surface resistance presents by far the tightest bottle-neck here. Some limitations of instrumentation and measurement were set by the extent of this particular project (budget and workforce limits, in particular), forcing some key approaches, such as infrared spectrometry, to be postponed, while other constraints were set by the production environment (e.g., resistance measurements are confined to time slots between shifts). Some quantities deemed relevant in the Ishikawa diagram cannot be measured with sufficient certainty. Wherever possible, we strove to either balance out such uncertainties by measuring across an entire spectrum of conditions (e.g., personnel rotation reduces fluctuation due to individual difference in typical skin resistance, skin flaking, etc.), or by keeping influencing factors constant (e.g., fixed product mix processed at the selected workstation).

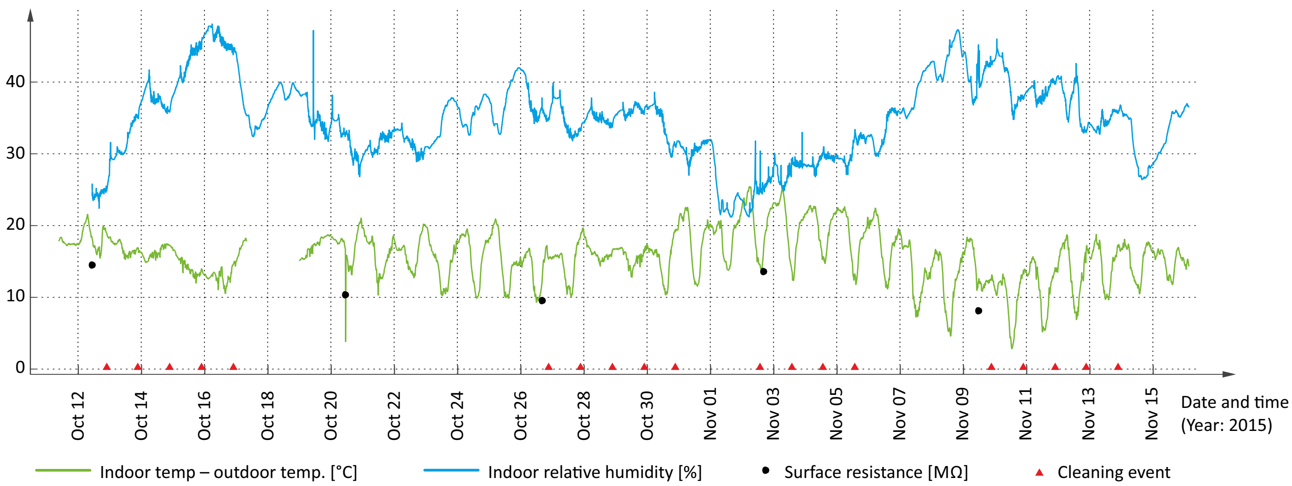

Fig. 3. Side-by-side view of the difference between indoor and outdoor temperature (green), indoor relative humidity (blue), and surface resistance (black circles). The triangles above the horizontal axis denote logged surface cleaning events.

IV. EVALUATION OF RAW DATA

Measurements have been taken on a regular basis since calendar week 35 of 2015, yielding ca. 500,000 scalar values until the time of writing the paper. A first examination of raw data does already confirm consistency of values of the same quantity measured by different sensors, and reveal simple relations. Neither indoor temperature nor relative humidity showed much variation across the factory airspace, suggesting that a facility-wide roll-out is likely to succeed with relatively few temperature and humidity measuring locations. The impact of the difference of indoor and outdoor temperature on indoor relative humidity is clearly recognizable, as is the effect of relative humidity on surface resistance which begins to rise at values below 30% (see Figure 3), both findings confirming previous industrial experience.

V. DATA PREPARATION AND MODELING

Two modeling subtasks were foreseen for this R&D project, examining (1) the dependence of floating dust density on other ambient conditions (indoor and outdoor temperature, and relative humidity) and work-dependent periodicity, and (2) the dependence of worksurface resistance on ambient conditions, cleaning events and work activity. In both cases, we looked back on pre-transformed measurement values and a fixed set of their statistical features aggregated over selected time intervals. In order to model accumulation and saturation processes of worksurface deposits, elapsed time and floating dust density integrated since the last cleaning event were also added to the data set. In the case of dust density estimation, possible work-related periodicity was taken into account by inserting the number of the current hour, shift, workday and week (as an incremented index) into the data set. The sparse sampling of resistance values did not allow the latter indexing in the case of surface resistance modeling. In order to include position-dependent characteristics of surface resistance, the two location indices of the measurement points ($\{A \ldots E\}$, $\{1 \ldots 4\}$ in Figure 1) were added as mandatory inputs to the resistance model.

For building the models and finding relevant dependencies, a *feature selection* method was used [20]. In this approach, an incrementally growing set of input variables is evaluated with a statistical measure based on Euclidean distance. In each pass, one more candidate input is added, and the impact of the current set of variables on the output variable (dust density or surface resistance, in our case) is measured. Having repeated this for all candidate inputs of the same pass, the input with the largest effect on the output variable is selected as the most relevant of all remaining candidates, and is permanently added to the set of inputs. In the next pass, the same concurrent procedure is executed again for the remaining candidates. At the end of the procedure, inputs and related dependencies are ranked by relevance, allowing the number of inputs to be trimmed.

After this stage, Artificial Neural Network (ANN) models can be fitted on the first n variables ($n_{\max} = 75$ or $n_{\max} = 50$ in our case) to estimate the output variable. The models can be ordered by their number of inputs increasingly, and the model accuracy can be analyzed to see how many input variables are necessary to reach a point where the model error cannot be lowered significantly by adding more input variables. Figures 5 and 6 show the graph of model errors based on the number of inputs.

Models for floating dust density estimations were prepared for current value, and prediction windows of the next hour, next shift, and next day. Average error rates of 5–8% were attained with the 50 best input variables, and reason-

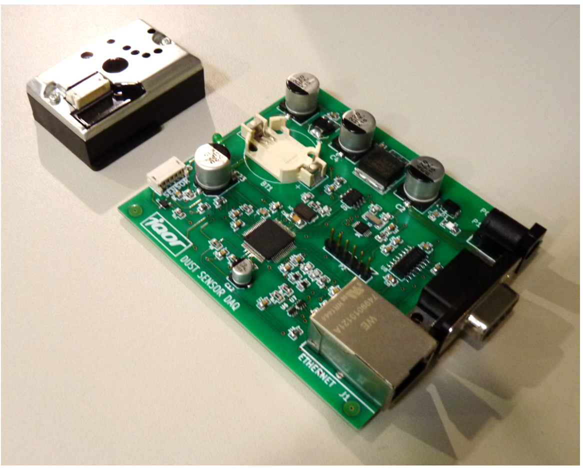

Fig. 4. Example of logging device (bottom right) and dust density sensor (top left)

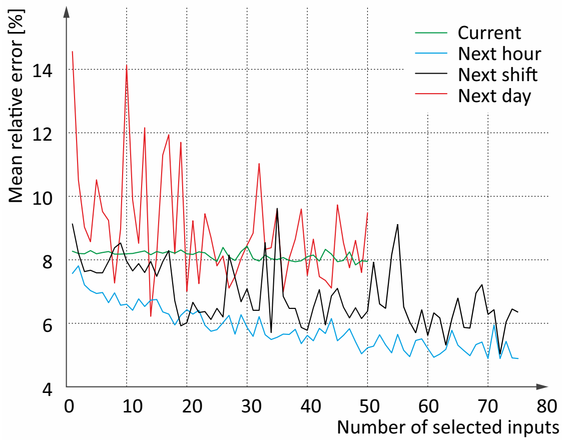

Fig. 5. Error rates of models estimating dust density for different time windows, in dependence of the number of most relevant input variables selected

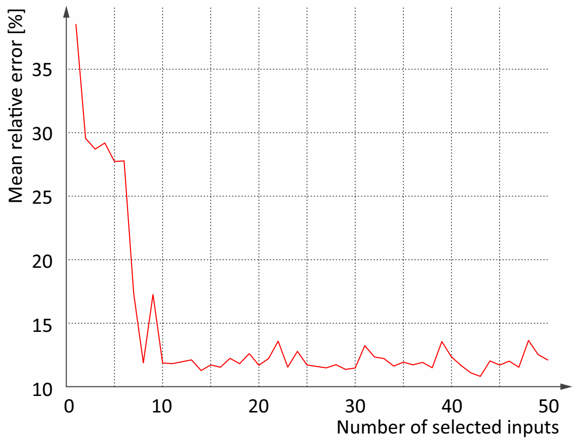

Fig. 6. Error rate of the model estimating worksurface resistance, in dependence of the number of most relevant input variables selected

ably close results (6–8% error) were reached with the most relevant 10–15 inputs. For all of the dust density estimations, statistical features of previous dust densities were found most relevant, typically in the range of some shifts or days prior to estimation. Remarkable was also the presence of outdoor temperature values among the most relevant variables—at this point, this is assumed to be the effect of increased fan air stream in the air conditioned inner space when indoor and outdoor temperatures differ largely.

The surface resistance model showed an error around 12% already after including the 10 most relevant inputs, and did not improve much thereafter. The relative humidity values from the past 7 days were found to be of highest relevance, followed by outdoor temperature and dust density of preceding 3–7 days. As mentioned before, long-lasting low outdoor temperatures are known to deplete humidity of heated indoor spaces, and were found to have effect on dust density as well via increased fan air stream. Interestingly, effects of cleaning events were ranked 33rd and behind, possibly implying that resistance measurements were carried out too sparsely to capture their influence.

VI. NOVELTIES AND CONCLUSIONS

The paper presented first results of an R&D project in an area of industrial production that has rarely been in the focus of research, namely, the dependence of the surface resistance of ESD-protected worksurfaces on ambient conditions and work processes in an electronics assembly and repair context. An important characteristic of the research presented is its closeness to practical application—(1) existing industrial experience played a key role in outlining expected dependencies and setting up an instrumentation roadmap, and (2) results continue to be evaluated in the context of a possible roll-out in industrial production where measuring and intervention must align well with efficient manufacturing routine. Measured data of ambient conditions and surface resistance were examined by a feature selection method, revealing that surveying the ambient conditions for the preceding 3–7 days allows a resistance estimation with 12% relative error without relying on resistance measurement records from these intervals. *This allows surface resistance estimation with sensors that do not interfere with ongoing work processes,* although with limited accuracy. While these results alone already show that a model-based estimation tool is feasible, relevance rankings of cleaning times suggest that a more accurate model is likely to need more frequent resistance measurement, at least in the data collection phase.

While the potential relevance of optical (contactless) surface contamination measurement in ease of use and minimal impact on work activities was highlighted in the paper, limitations of the current project will leave it for later examination. Also, compliance with production processes has not allowed so far to leave the safe area of ambient parameters—follow-up research will have to include this option for better examination of the boundaries of safe work process conditions.

VII. Acknowledgment

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