Analysis of Detection Repeatability and Reproducibility Trials

Damir MARKUČIČ, Biserka RUNJE, Vedran MUDRONJA, Sanjin MAHOVIĆ,
University of Zagreb, Department of Quality, Croatia

Abstract. R&R analysis of results of mine detection trials is presented. Data for R&R analysis has been obtained by means of round robin trials which comprehend different operators, instruments and targets determined by various parameters like type of mine, depth and type of soil in which mine is burried.

R&R analysis shows quantitative measure of detection process in certain conditions. Beside information which could be achieved through estimating probability of detetction (PoD) R&R analysis describes to which extent the particular detection process is consistent or uncertain. The aim of R&R analysis of detection is to contribute to the general analysis and assessment of detection reliability.

Introduction

Repeatability and reproducibility (R&R) studies are commonly utilised in analyses of capability of processes. In this article we apply R&R on the results of pinpointing the buried mines (parts) for the purpose of statistical R&R analysis of mine detection process.

Results obtained from R&R analysis are compared with conventional halo size (± 10 cm) representing circle area around true position of the mine in which it is expected to get response (true-positive detection) form the mine utilising mine detectors.

In particular, we take the raw data (results of pinpointing in X-Y coordinate system) obtained by operators and the true positions of buried mines. Calculated distance of a pinpointed result from a true mine's position is referred as a radial distance.

The results were obtained as a part of trials performed on the test field near Benkovac, Croatia, during May 2005.

Measurements of the system capability are based on analysis of repeatability and reproducibility of measuring system in which one utilises *The Range & Average Method* (also known as *Long Method* in literature).

The *Range & Average Method* computes the total measurement system variability, and allows the total measurement system variability to be separated into repeatability, reproducibility, and part variation.

Repeatability (Equipment variation) is the variability of the measurements obtained by one operator while measuring the same item repeatedly. This is also known as the inherent precision of the measurement equipment (device).

Reproducibility (Appraiser variation) is the variability of the measurement system caused by differences in operators' performances. Mathematically, it is the variability of the average values obtained by several operators while measuring the same item.

Total measurement variability, *combined R&R*, combines repeatability and reproducibility.

Total variation (TV) is a sum of variations which are caused by combined R&R (measurement equipment and appraisers) and parts.

Estimation of measurement system capability is shown as ratio between R&R and total variation (TV). If tolerance interval (T) is given then system capability can be evaluated as ratio between R&R and tolerance. Tolerance interval (T) is interval determined between the upper and the lower specification limits.

2. Design of pinpointing trials

Certain pairs of an operator (**appraiser**) and a metal detector device (**equipment**) forms "**system**". Eight combinations (pairs) forming diverse systems were taken from existing round robin trials. The system provides a series of results by a run through a part of a given Lane, as presented in Table 1. Three repetitive runs were performed in order to obtain 3 repetitions for repeatability analysis. Graphical presentation of results thereby obtained is shown in Figure 1.

Table 1. Systems formed by operator-device pairs and runs through Lanes.

Run		**1**		**2**		**3**		**4**		**5**		**6**		**7**		**8**	
System		*operator*	*device*	*operator*	*device*	*operator*	*device*	*operator*	*device*	*operator*	*device*	*operator*	*device*	*operator*	*device*	*operator*	*device*
Lane	**2**	**A**	**U**	**C**	**Z**	**D**	**Y**	**B**	**X**	**A**	**Z**	**B**	**Y**	**D**	**X**	**C**	**U**
	4	**D**	**Y**	**B**	**X**	**A**	**U**	**C**	**Z**	**D**	**X**	**C**	**U**	**A**	**Z**	**B**	**Y**

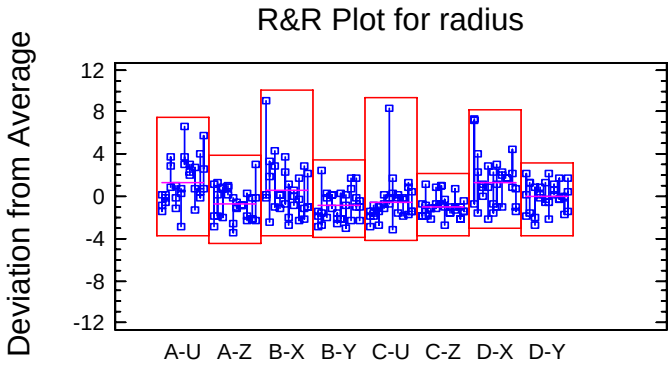

Figure 1. Representation of all data in trials.

Lane 2 represents uncooperative soil, while Lane 4 represents cooperative soil. During runs, Lanes were scanned partially. The lengths of each of the parts in Lane 2 and Lane 4 were approximately 3,5 m and contained 5 buried mines each. Types, depths and true positions of mines are given in Table 2 and Table 3. Additionally, each mine (**part**) was attributed the unique code (# mine). These codes are also specified in these two Tables.

Table 2. Targets buried in **Lane 2** (uncooperative soil).

mine	depth (cm)	**true position** x (cm)	y (cm)	**targets** *mine code*
PMA-2	0	69	50	*# 20*
PMA-2	5	17	80	*# 25*
PMA-2	5	19	151	*# 26*
PMA-1A	10	79	288	*# 10*
PMA-1A	5	35	343	*# 5*

Table 3. Targets buried in **Lane 4** (cooperative soil).

mine	depth (cm)	true position x (cm)	true position y (cm)	targets *mine code*
PMA-2	0	85	2266	*# 22*
PMA-2	5	23	2288	*# 29*
PMA-1A	5	60	2482	*# 9*
PMA-1A	10	14	2538	*# 13*
PMA-1A	15	77	2546	*# 19*

3. R&R analysis

To gain quantitative perception of pinpointing process the following R&R analysis comprises all data obtained by all eight systems (Table 1), pinpointing all ten parts (mines shown in Table 2 and Table 3) in both Lanes (2 and 4). The summary of obtained results is in Table 4.

Table 4. Analysis Summary.

	Estimated sigma (cm)	Estimated Variance (cm)	Percentage
Repeatability	1,69543	2,87449	85,23
Reproducibility	0,70565	0,49794	14,77
R & R	1,83642	3,37243	100,00
Parts	1,13756	1,29404	

On the basis of the study involving 8 systems, each pinpointing 10 parts 3 times, the estimated standard deviation of the observed process for radial distance equals 1,8 cm. Of the total variance, 14,77 % is due to differences between operators, while 85,23 % is due to differences between devices. The former is a contribution of the reproducibility, and the later of repeatability. In last column in Table 4, sum of both contributions, repeatability and reproducibility make 100 %, which is another way of expressing the idea that reproducibility and repeatability are analysed as contributions to R&R.

Row belonging to parts is contribution to total variation (TV) caused by differences between measured parts and excluded from R&R.

Table 5. Variation Study and 95,0 % confidence intervals (Lower nad Upper Limits) for 6 std.dev.

	Lower Limit, cm	**6 std. dev., cm**	Upper Limit, cm	Contribution, %
Repeatability	9,12638	**10,1726**	11,4920	61,60
Reproducibility	2,74853	**4,2339**	9,1081	10,67
R & R	9,90649	**11,0185**	12,4141	**72,27**
Parts	4,58247	**6,8254**	13,2956	**27,73**

Table 5 shows intervals equal to 6 times the standard deviations due to repeatability, reproducibility, combined R&R, and variability between parts. These intervals can be expected to contain 99,73 % of the errors attributed to each source. Total variation is studied, hence R&R and variation of parts both make 100 %. Within total variation (TV) it is apparent that reproducibility contribution (due to the operator variation) in comparison with parts contribution is more than two times smaller.

It is expected the values of radial distance to deviate from the true positions by **± 5,5 cm** due to combined R&R, an **interval 11,0 cm wide** what is quite within conventional halo size (± 10 cm).

Comparing the variability of the pinpointing process to the overall variability in radial distances, the pinpointing process contributes 72,27 % with the remaining 27,73 % attributable to differences amongst parts. Since the estimates of variability are subject to sampling error, the confidence intervals show how precise these estimates are (Table 5).

Given a tolerance (specification named "halo") 20,0 cm wide (thus the radius of 10,0 cm), the variability from the observed process can be expected **to cover 55,1 % of that range** while additional 34,1 % variability contribution can be expected caused by parts (mines) as implicated by the trials.

Table 6. Tolerance interval analysis - Tolerance (halo size) = 20,0 cm

	Percent of Tolerance
Repeatability	50,86
Reproducibility	21,17
R&R	**55,09**
Parts	**34,13**

4. R&R analysis regarding devices

In order to infer about capabilities of each device utilised in the trials additional R&R studies have been performed. The results should be evaluated only within the scope of the study and are not to be extracted and generalised without context. Data sets for each device were extracted and they contain results obtained by certain pair of operators, Table 7.

Data in Table 7 are expressed as scalar, radial quantities. This approach is more suitable and convenient to interpreting and realising the influence of particular elements.

In Table 7, it is seen that variability contribution of differences between devices (repeatability) is in all four cases larger than the contribution of other elements in the pinpointing (detection) system (operators, mines, etc.). That strengthens the guideline that in future, regarding precision of pinpointing, the emphasis should be put on improvement of devices. That is the general trend observed for all devices.

It is also indicative that device Z which exhibits the smallest repeatability standard deviation at the same time reveals no reproducibility deviation.

Table 7. R&R analysis summary - devices.

	device X B & D operators		**device Y** B & D operators		**device Z** A & C operators		**device U** A & C operators	
	Estimated Sigma	Percent of Total	Estimated Sigma	Percent of Total	Estimated Sigma	Percent of Total	Estimated Sigma	Percent of Total
Repeatability	2,36	98,38	1,51	86,56	1,21	100,00	1,66	62,79
Reproduci-bility	0,30	1,62	0,60	13,44	0,0	0,00	1,28	37,21
R & R	2,38	100,00	1,63	100,00	1,21	100,00	2,10	100,00
Parts	1,44		0,90		1,06		1,64	
	6,0 Std. dev.	Contribution, %	6,0 Std. dev.	Contribution, %	6,0 Std. dev.	Contribution, %	6,0 Std. dev.	Contribution, %
Repeatability	14,14	71,93	9,09	66,44	7,28	56,68	9,97	39,02
Reproduci-bility	1,82	1,19	3,58	10,32	0,0	0,00	7,67	23,12
R & R	14,26	73,12	9,77	76,77	7,28	56,68	12,58	62,14
Parts	8,65	26,88	5,37	23,23	6,37	43,32	9,82	37,86

However, on the basis of results obtained different level of influence of other elements may be seen. E.g., the **minimal and maximal percents of total variations of reproducibility** are observed in case of **devices Z and U**, respectively. Having in mind that these two devices were exploited in the trials by the same pair of operators (thus affecting reproducibility), it is rather unexpected that such a difference in performance between two operators (A and C) occurs between series of pinpointing using two devices (Z and U).

An observation of the results of runs, presented in the Figure 2, reveals that one result (5th run) obtained by **operator C with device U** significantly differs from other outcomes, thus significantly affecting reproducibility in this particular case in comparison with other arrangements. For completeness, the corresponding data for operators B and D are shown in Figure 3. Anyhow, it is opportune to treat the interaction of operators and devices in more detail.

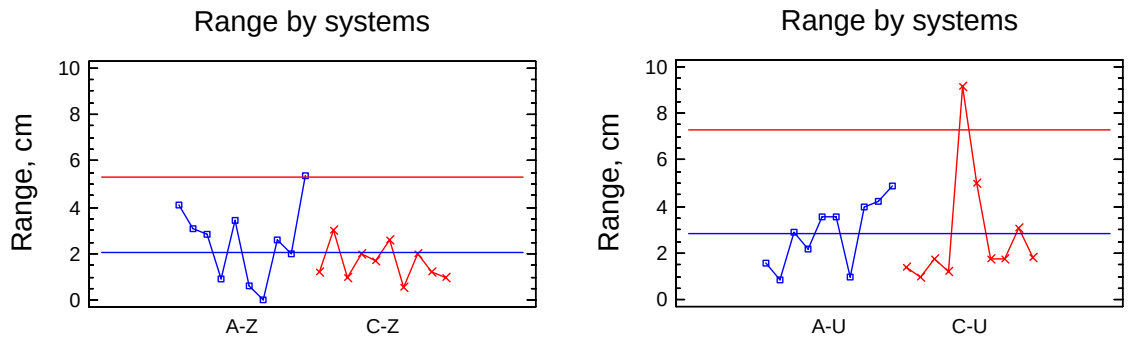

Figure 2. Ranges of pinpointing results (3 repetitions) for each of 10 targets obtained by **operators A and C** using **devices Z and U**.

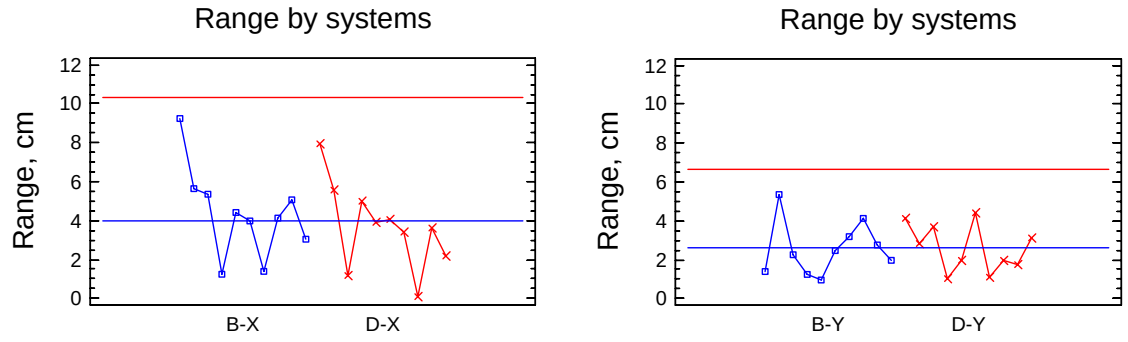

Figure 3. Ranges of pinpointing results (3 repetitions) for each of 10 targets obtained by **operators B and D** using **devices X and Y**.

Additionally, repeatability and reproducibility, as well as combined R&R, for **devices Y and Z** are of the smallest amount between all four devices, while performances with **devices X and U** demonstrate wider intervals due to combined R&R at the same time with the larger parts contribution to variation.

Table 8. Tolerance interval analysis - devices.

	device X B & D operators	**device Y** B & D operators	**device Z** A & C operators	**device U** A & C operators
	Percent of Tolerance	Percent of Tolerance	Percent of Tolerance	Percent of Tolerance
Repeatability	70,72	45,44	36,41	49,84
Reproducibility	9,09	17,91	0,0	38,37
R & R	71,31	48,85	36,41	62,89
Parts	43,23	26,87	31,84	49,09
Interval due to combined R&R, cm	**± 7,13**	**± 4,88**	**± 3,64**	**± 6,29**
Average deviation; (x, y) in cm	(1.78, -0.55)	(1.20, 0.98)	(0.70, 1.42)	(1.28, 1.38)

Intervals due to combined R&R in Table 8 are considered as scalar, radial distance, while average deviations denotes points in rectangular co-ordinate system (x, y) which stand for

average position of pinpointing results in reference to the true positions of mines. This makes possible stronger relating of analysis results with the underlying experimental set-up.

Graphical presentation of average value of determined position (pinpointing) with accompanied R&R interval (six standard deviations of combined R&R) for each of four devices, is shown in Figure 4. All intervals due to combined R&R are within halo size.

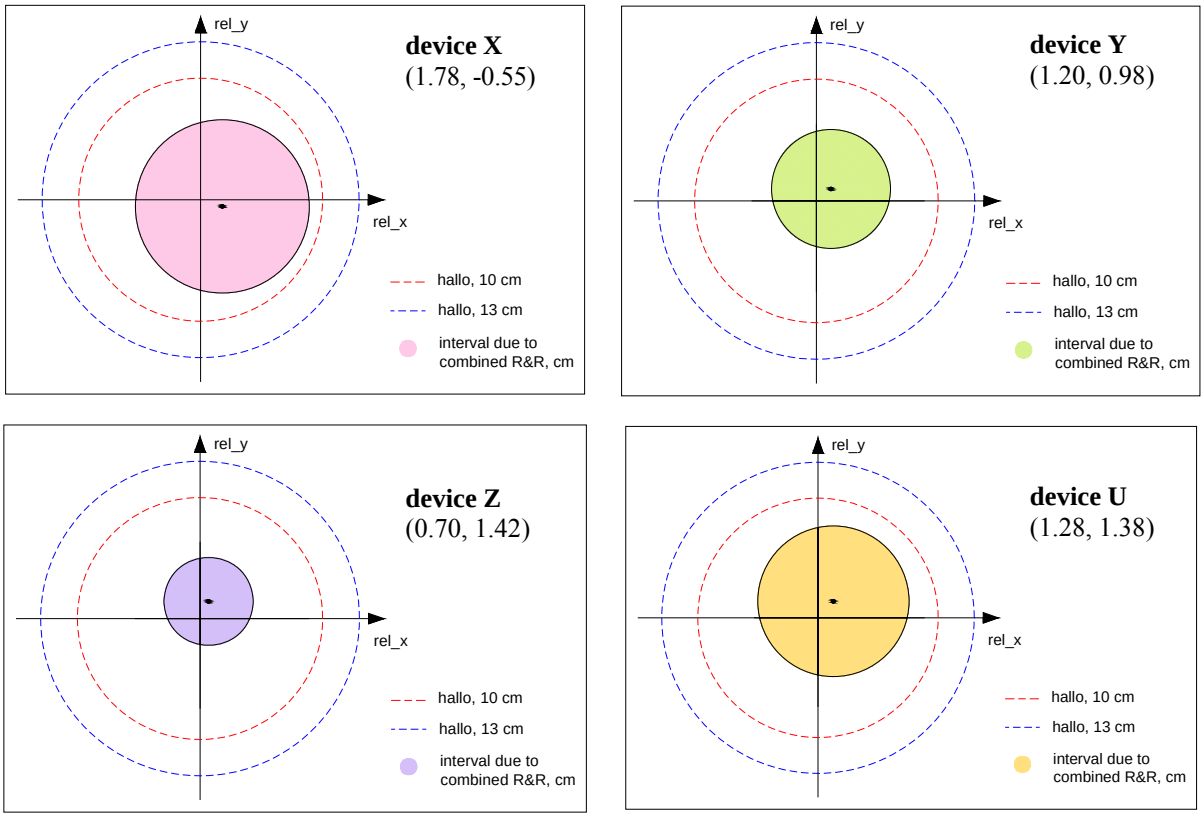

Figure 4. Presentation of intervals due to combined R&R for the four devices. Determined positions (circles' centres) and true positions (origins of co-ordinate systems) are shown. Numbers in parentheses denote (x, y) co-ordinates (circles' centres) of average values of pinpointing results, measured in centimetres. Diameters of filled circles equal six standard deviations of combined R&R. Dashed red (blue) circle denotes halo radius of 10 cm (13 cm), with centre in origin of co-ordinate system.

5. Conclusions

The repeatability and reproducibility analyses have shown large potential of the R&R study in improving the test and evaluation of metal detectors. On the basis of results of R&R analysis regarding pinpointing of the buried mines by means of metal detectors (devices) considering performed trials, the following conclusions would appear:

- R&R analysis is capable of differentiating between significant components of the analysed set-ups.
- Larger variances are due to the differences between devices (repeatability) rather than due to differences between operators (reproducibility). That contributes to the recognition that devices are the part of pinpointing (detection) process causing most of the observed variations. The recognition points to further research and development oriented toward minimising of that component. This is found to be the largest potential improvement.
- The conventional halo size (± 10 cm) appears to be inadequate for devices X and U in the case if there is an agreement that system capability of pinpointing process should

cover not more than 66,6 % of given tolerance interval (Cp = 1,5) assuming that halo size is presenting this interval.

- We propose that consideration should be given to the possibility to estimate halo size for specific arrangements (soil, device and mines) comprehending appropriate range of relevant parameters or characteristics.