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Machine-integrated Magnetic Collector Design and Testing

The Geneva International Centre for Humanitarian Demining led a test program to evaluate a machine-integrated magnetic collection system. Promising results suggest it could speed up manual follow-up activities and provide valuable data during technical survey operations.

by Erik de Brun [GICHD Consultant] and Stephen Ahnert [GICHD Consultant]

In 2011 and 2012, the Geneva International Centre for Humanitarian Demining (GICHD) led a test program to evaluate the feasibility and effectiveness of a mechanical demining, machine-integrated magnetic collector designed to collect ferrous metal debris during flailing operations. The purposes of this integration and test effort were to determine if

- A machine-integrated magnet would collect metal debris during flailing operations
- A machine-integrated magnet would increase the efficiency of demining operations by speeding up manual follow-up (especially when working in an area with high metal contamination)
- Collected debris could be utilized to support technical survey operations

Together, the GICHD and DOK-ING designed a magnetic collection system and integrated it with an MV-4 flail. In March 2012, the authors, along with other team members from the Swedish Explosive Ordnance Disposal and Demining Center (SWEDEC) and DOK-ING, conducted functional and statistical testing in Zagreb, Croatia. During functional testing, the setup and configuration of the magnetic collection system was optimized and subsequently utilized for statistical testing. The statistical testing results were very promising, with 44% (240 of 544) of the seeded ferrous debris recovered during the first pass of the machine and 34% (102 of 304) of the remaining debris recovered on the second pass. In the end, 68% (371 of 544) of the seeded debris was collected. Although the testing was only conducted in one set of conditions and utilized seeded debris, the collection percentages are sufficiently high to suggest that a machine-integrated magnetic collector could dramatically reduce the amount of ferrous material remaining in the field following flailing operations. If results hold in field conditions, this methodology could dramatically speed up manual follow-up activities and provide valuable data during technical survey operations.

Introduction

Mechanical demining systems can greatly increase the effectiveness, safety and efficiency of mine-clearance operations. They clear or release large areas more quickly and safely than manual demining alone. In most cases, national standards require some form of manual follow-up after machine clearance, which can range from visual inspection to full manual clearance requiring the removal of all metal debris. When 100% metal-free clearance is required or when operating in areas heavily contaminated with ferrous material, follow-up manual clearance can be painstakingly slow because every metal detector indication must be investigated.

GICHD recognizes that, combined with mechanical tools or as stand-alone assets, magnets can increase manual clearance productivity by removing ferrous metal debris from the clearance area. In addition, the collection of metal debris can provide invaluable information about the type and location of contamination during technical survey and clearance operations. Ideally, magnet-equipped machines would collect a large percentage of the metal contamination in a given area, increasing overall operational efficiency.

Figure 1. DOK-ING MV-4 utilized during testing.
All graphics courtesy of the authors/GICHD.

GICHD previously tested a combined flail and magnet system using a Bozena 5 that towed a permanent magnet. An operational assessment was conducted in Azerbaijan between January and March 2010. The towed magnet picked up some ferrous debris, and recovery effectiveness was very low overall. A full report on the testing can be obtained from GICHD.[1] Based on that testing's results, several improvements to the magnetic collector design and configuration were hypothesized, and DOK-ING was contracted to assist with design and construction of a revised magnetic collector that would be integrated directly with the machine flail head. This article documents the testing that GICHD conducted at DOK-ING's manufacturing facility in Zagreb, Croatia, in March 2012.

Materials and Location

The following testing equipment was used:

DOK-ING MV-4. Two separate MV-4 machines with flail attachments were utilized during testing.

Magnetic roller. A magnetic roller was one component of the magnetic collection system. Measuring 220 mm in diameter and 1,740 mm wide, it was installed directly behind the flail head (Figure 2, page 53). On each roller's side, teeth ensured that it rotated as the machine advanced. The roller height relative to the flail was adjustable. The roller contained

Figure 2. Magnetic roller attachment.

Figure 3. Magnetic sheet attachment.

242 neodymium permanent magnets (each 42 mm by 40 mm by 6 mm) spaced evenly, adhered directly to the base metal roller and covered with an abrasion-resistant rubber. Field strength of the magnets was 0.17 Tesla on the dorsal and ventral faces, and 0.34 Tesla on the lateral faces.

Magnetic sheet. Another component of the magnetic collection system was a magnetic sheet (Figure 3 above) that was mounted behind the flail head in place of the chain guard. The sheet was 1,740 mm wide by 500 mm tall with magnets present in the lower two-thirds. The sheet contained 175 neodymium magnets evenly spaced in a 5-by-35 grid covered with an abrasion-resistant rubber coating, yielding an overall field strength of 0.2 Tesla at the sheet surface.

Magnetic upper catch. In addition to the magnetic roller and sheet, a magnetic catch was installed along the front edge of the flail shroud, above the flail head (Figure 4 right). This upper catch was designed to capture magnetic debris thrown forward by the flail hammers. The magnetic catch was constructed similarly to the sheet but contained only a single row of magnets.

Ferrous debris. Various types of ferrous debris (Figure 5, page 54) were used to seed the test lane. The debris elements were selected to reflect the size and shape of ferrous debris that would typically be recovered during actual clearance operations. Table 1 (page 55) lists the different types of material used during the testing.

Testing was performed in a prepared lane at DOK-ING's main production facility in Zagreb. The test lane was approximately 45 m long, 4 m wide, 0.5 m deep and filled with relatively fine riverbed sand (Figure 6, page 54).

Figure 4. Magnetic upper catch attachment.

With the weather clear, temperatures ranged between 18 C and 22 C during the test period. The sand was dry throughout the tests and was not compacted beyond the compression provided by the MV-4 tracks. Rakes were used between tests to level the sand as necessary, and a bulldozer periodically leveled the lane.

Testing Procedures

The testing was divided into two separate phases: functional/experimental testing and statistical testing. During the functional tests, the setup and configuration of the magnetic collection system was varied in order to identify the most effective arrangement. Each setup was tested using different seeding materials, flail rotational speeds, machine speeds and working depths in order to identify the effects of these variables on the effectiveness of the different configurations. Once the most effective configuration was identified, the focus shifted to statistical testing. The statistical testing focused on generating a consistent, statistically significant data set from which debris-recovery percentages could be estimated.

Functional tests. A number of functional tests were performed to evaluate and optimize the magnetic collection system's performance.

- Series 1: surface-laid debris recovery without the flail spinning
- Series 2, 4 and 6: magnetic-sheet evaluation and configuration optimization
- Series 3 and 5: magnetic-roller evaluation and configuration optimization
- Series 7: full magnetic collection system optimization (roller, sheet and upper catch)

Statistical tests. Based on the results of the functional testing, the following magnetic collection system and machine configuration (Figure 7, page 55) was used for all of the statistical tests:

- Magnetic sheet hanging immediately behind the roller with chains controlling the orientation
- Magnetic-sheet, upper-catch and magnetic-roller setup on same MV-4
- Machine-operating parameters set at a working depth of approximately 15 cm, a machine speed of approximately 1.5 km/h and a flail-head speed of approximately 450 rpm (50% of maximum)
- Roller placed in its lowest position (centerline of roller approximately 5 cm above the flail skids)

The test lane was divided into four boxes, each approximately 7 m long, with a gap of approximately 4 m between each area. Each box was seeded with a specific set of ferrous debris (Table 2 page 55) . With 68 seeded targets in each of the four test boxes, there was a total of 272 seeded items for each test. Within each test box, debris was randomly seeded within a strip approximately 1.5 meters wide in the test lane's center. The debris was buried to varying depths up to 15 cm. The statistical test was performed twice. During the first test, the seeded debris was painted green; during the second test, the seeded debris was painted yellow so that any remaining debris from the first test that was collected during the second test could be identified and excluded from the results.

After completing each box in the first test, the flail was removed so that captured debris could be removed and recorded. After completing the initial pass through the four test boxes, displaced soil was pushed back into the flail track with rakes. In order to see what percentage of the remaining debris each test box could recover, this process was repeated without any additional reseeding or manual clearance. A third pass was also performed without stopping after each box.

Before the second test, a hand-held metal detector and shovels were used to find and remove as much of the remaining debris as possible. This manual-collection effort reduced the amount of contamination for subsequent tests and identified the approximate depth of the debris not recovered by the magnets.

The second statistical test procedure was very similar to the first test except that four passes were performed. During the third and fourth passes, the flail path was shifted slightly to the right and left, respectively, in order to process areas where soil was pushed out to the sides during the first and second passes.

Results of Functional Tests

The functional testing's main purpose was investigating each component of the magnetic collection system and determining the optimal configuration for the system as a whole. Initial testing with surface-laid debris showed that the debris is easily captured yet cannot be easily dislodged if it comes into contact with one of the magnetic collectors. Testing of the magnetic roller showed that collection was much more effective if the roller was set as low as possible (centerline of the roller was approximately 5 cm above the flail skids), allowing the roller to plow through the soil deposited just behind the flail head. As the machine advanced, the roller would push a large mound of soil ahead of it, causing flailed soil to be pushed back into the path of the upward-moving flail hammers. Forward soil ejection from the top of the flail shield increased dramatically compared to previous

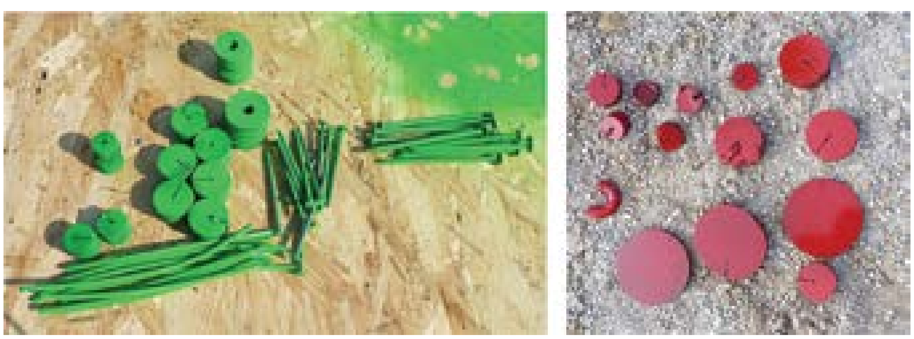

Figure 5. Ferrous debris utilized during testing.

Figure 6. Test lane and close-up of soil.

Figure 7. Machine setup for statistical testing.

ID	Description	OD	ID	Thickness/ Length	Mass
1	Large Washer	28.0 mm	6.7 mm	2.0 mm	8.6 g
2	Medium Washer	20.0 mm	10.5 mm	2.0 mm	3.1 g
3	Small Washer	15.0 mm	3.0 mm	2.0 mm	2.6 g
4	Large Nail	3.4 mm		78.0 mm	5.7 g
5	Small Nail	2.8 mm		58.0 mm	3.1 g
6	Wire	3.0 mm		100–150 mm	7.5 g
7	Medium Slug	24.0 mm		15.0 mm	55 g
8	Small Slug	16.0 mm		15.0 mm	21 g
9	Large Slug	>30.0 mm		5–15 mm	36–382 g

Table 1. Characteristics of seeded ferrous debris.

ID	Description	Qty
1	Large Washer	12
2	Medium Washer	12
3	Small Washer	12
4	Large Nail	12
5	Small Nail	12
6	Wire	12
7	Medium Slug	6
8	Small Slug	2
	Total	68

Table 2. Seeded debris in each test box (type and quantity).

tests, and a substantial amount of soil flowed over the top of the roller (Figure 8, page 56). As a result of the soil flow over the roller, the recovery percentage was dramatically higher than previous tests (30–50% recovery), and additional passes through the same test area continued recovering substantial debris.

The magnetic sheet alone was not very effective (capturing up to 20% of the debris), but the collection effectiveness was increased dramatically when placed just behind the roller due to the amount of soil contact. In addition to the magnetic collection system configurations, many operational variables, including fail speed and machine speed, were also investigated.

Based on testing, the optimal magnetic collection system configuration consisted of the magnetic roller placed in its lowest position, the magnetic sheet positioned directly behind the roller and the upper catch placed at the front of the flail shield (Figure 9, page 56). All subsequent statistical testing utilized this configuration.

Results of Statistical Tests

The optimized magnetic collection system configuration (Figure 10, page 56) utilized during the statistical testing proved quite effective. During the two combined statistical tests, 44% (240 of 544) of the seeded debris was recovered on the first pass, and 34% (102 of 304) of the remaining debris was recovered on the second pass. The collection effectiveness decreased significantly to 8% (17 of 202) of the remaining debris for the third pass. Figure 11 (page 57) shows the percentage of available debris recovered during each pass, separated by debris type. In general, a similar debris percentage was recovered on each pass, regardless of debris type.

In addition to the quantity of each debris type, the recovery location (roller, sheet or catch) of the debris was also recorded and analyzed. Figure 12 (page 57) shows the breakdown of recovery location, separated by debris type. For the lighter types (washers, nails, wires), the roller collected the majority of the debris (50% on the roller, 26% on the upper catch and 24% on the sheet). However, for the larger, heavier debris types (medium and small slugs), the percentages shifted dramatically with 34% collected on the roller, 65% on the upper catch and 2% on the sheet. One potential explanation for this difference is that a direct hit from one of the upward-swinging flail hammers could impart enough momentum to free a slug from the surrounding soil and send it to the upper catch, whereas the smaller debris types are less likely to encounter direct hits from the flail hammers and are slowed more dramatically by the surrounding soil due to their shape and smaller inertia.

In general, all three components of the statistical test configuration contributed significantly to the overall recovery effectiveness, which suggests that placing magnets in multiple locations around the flail head yields higher collection percentages.

Following the completion of the statistical testing, a purely qualitative test was performed in a topsoil area contaminated with ferrous material adjacent to an industrial warehouse and machine shop. A section approximately 2 m in length was flailed to a depth of 15 cm. As seen in Figure 13 (page 57), several handfuls of metal debris, ranging from small particles to large chunks, were collected. The result, while purely qualitative in nature, suggests that the configuration

Figure 8. Increased soil turbulence with magnetic roller in lowest position.

Figure 9. Optimal configuration of the magnetic collection system.

Figure 10. Statistical test run.

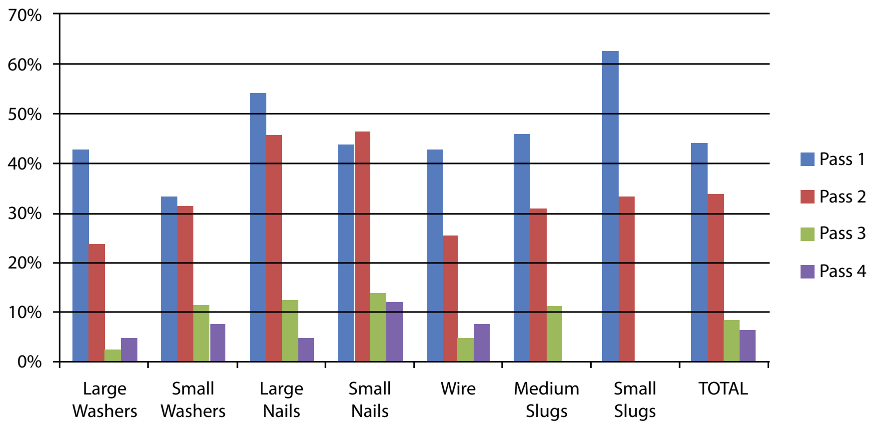

Figure 11. Percentage of remaining debris collected by pass.

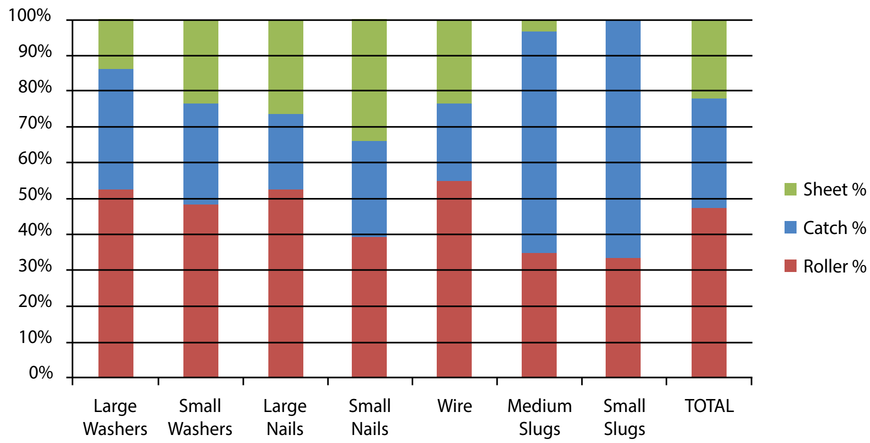

Figure 12. Location of breakdown of collected debris.

Figure 13. Qualitative topsoil test and collected debris.

may be effective in soil conditions other than dry, loose sand. It also shows that magnets are effective at capturing ferrous debris covered with substantial oxidation and other surface contamination conditions likely to be found in the field.

Discussion

The testing showed that machine-integrated permanent magnets can be effective in collecting ferrous debris (during testing, more than 40% of seeded debris was collected on the first pass). Although the testing was conducted in dry, loose sand using seeded debris, the collection percentages are sufficiently high to suggest that machine-integrated magnets could dramatically reduce the amount of ferrous material remaining in the field following flailing operations. Reducing the number of metal-detector indications during manual follow-up can significantly increase deminer speed, which improves the overall efficiency of clearance operations. The results also suggest that machine-integrated magnets can provide beneficial data on minefield contamination when used during technical survey operations.

Soil/magnet contact. The testing showed that the action of the flail hammers tended to deposit metal debris in the loose soil behind the flail and the majority of the debris remained below the surface of the flailed soil. Since permanent magnets do not typically have sufficient strength to pull material through a substantial amount of soil, magnetic configurations passing over the top of the loose soil recover only a small fraction of the debris. Because of this, magnetic collectors pulled behind machines have very low effectiveness. In order to increase collection effectiveness, raising the percentage of the soil that comes into direct contact with the magnetic surface is necessary. With the magnet geometries available during this test period, the most effective method involved placing the roller in its lowest position. The resulting configuration caused soil to flow over the roller and dramatically increased the amount of soil thrown up toward the sheet and the upper catch, which substantially raised the percentage of soil and debris that came into direct contact with the magnetic surfaces.

Debris removal. Once the debris adhered to the magnets, removal was relatively time-consuming. The magnets did not include any provision for wholesale removal of the debris, so pieces were removed individually by hand. While this was acceptable for testing, during actual clearance operations in heavily contaminated areas, metal debris accumulation may be so rapid that the magnets must be cleared at frequent intervals to the point where area processing speed would be adversely affected by time-consuming debris removal.

Conclusion

The results of the testing suggest that machine-integrated permanent magnets can be effective at capturing ferrous debris during flailing operations. However, after observing the movement of the debris-filled soil during testing, the test configuration could clearly be further optimized to improve debris collection. The flail shroud could be designed to efficiently guide the soil deposited behind the flail head to the magnetic collection area. A ramped surface immediately behind the flail head (in place of the roller) would allow soil to be thrown upward and funneled into channels, maximizing its exposure to magnetic surfaces. A larger upper catch would further improve collection effectiveness. In addition, any integrated magnetic collector must include provisions to easily clear debris from the collection surfaces.

Once the magnetic collection system is redesigned, additional testing in a controlled environment (such as SWEDEC) and a representative field environment (such as an actual minefield or known battle area) is recommended. The focus for these tests should be

- To determine what impact ferrous debris collection has on the efficiency of manual follow-up clearance
- To determine what impact ferrous debris collection has on technical survey operations
- To develop operational procedures for working with a machine-integrated magnetic collector

With additional input from field testing, machine-integrated magnetic debris collection could dramatically speed up manual follow-up activities and provide valuable data during technical survey operations.

See endnotes page 67

Erik de Brun is a partner and co-founder of Ripple Design. He is involved in the design, development, testing, and manufacturing of mechanical demining equipment as well as the management of demining operations. Prior to founding Ripple Design, de Brun designed and tested armored vehicles with BAE Systems and V-22 Osprey flight-control software with Boeing Rotorcraft. He holds a Master of Science in mechanical engineering and applied mechanics from the University of Pennsylvania (U.S.) and a Bachelor of Science in mechanical and aerospace engineering from Princeton University (U.S.).

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