Multi-objective Optimization Using Genetic Algorithms to Design the Optimal Excavator. J. P. Kenrick[1], [1]Lunar Outpost, Inc. (17700 S. Golden Rd. #102 Golden, CO 80401, joseph@lunaroutpost.com).

Introduction: Multi-objective formulations enable optimization of realistic, complex engineering problems. Often, objectives under consideration in these problems conflict with each other. This prevents simultaneous optimization of each objective and can yield unacceptable results. Multi-objective optimization provides a way to generate a set of solutions that each satisfy the target objectives. Genetic algorithms can be used to find the optimal input parameters to maximize or minimize the target objectives. The problem of focus is to design the optimal excavation rover by minimizing the mass of the rover, maximizing the excavator's scoop volume, maximizing the power efficiency, and maximizing the net forward thrust the rover can generate. The tunable input parameters and the objective net forward thrust are based on the Bekker and Baylonev equations for draft force generation and excavation force required, respectively.

Multi-objective Optimization: Consider a problem that aims to optimize non-commensurable, indifferent objectives. The optimization problem aims to find solutions that minimize the set of objective functions. The solution set of decision variables is restricted by a series of constraints and bounds that narrow the solution space. Simultaneously optimizing each objective function to yield a perfect multi-objective solution is near impossible. Consequently, this optimization technique aims to yield a set of reasonable solutions, such that no solution is dominated by another solution. The non-dominated solution set cannot improve one objective without worsening another objective. This solution set is referred to as a Pareto optimal set, and all the possible dominant solutions sets lie on a *n*-dimensional Pareto front. The goal, therefore, of multi-objective optimization is to yield the Pareto front [1].

Genetic Algorithms: The genetic algorithm process was inspired by the evolutionary process of natural selection. Evolution favors the stronger species with respect to their environment's fitness function. Over time, the stronger species will therefore become the dominant species in the population. The genes of each species are passed on through a process called crossover. Occasionally, a gene can randomly mutate, and if the gene is favored in terms of the fitness function, it survives and yields a new species. Unsuccessful crossovers and mutations are eventually eliminated by natural selection. The genetic algorithm process used to identify a dominant solution set works in the same way.

There are two primary advantages of using genetic algorithms over conventional methods. The first is that it enables a population-to-population approach versus the conventional method of point-to-point. In other words, a range of possible solutions can be evaluated simultaneously rather than individually. The second advantage is that the globally optimal solution can be found. Traditional optimization methods, such as gradient descent, can only guarantee the local minima or maxima is found for the given problem.

Problem Formulation: The multi-objective optimization explored in this study was to design the optimal lunar excavator considering the conflicting objectives of minimizing mass, maximizing the forward thrust generated by the rover, maximizing the excavation volume, and therefore rate, and maximining the power efficiency.

Mass is often the most important constraint or requirement when designing a space system given the direct relation to cost. For successful excavation, a digging tool needs to be able to push into the ground without pushing the excavator off the surface. In addition, the excavator needs to be able to push or pull laterally without slipping across the surface. The resulting forward force that an excavator can generate is called the net thrust. Designing a low mass excavator that can still generate a positive net thrust are two of the objectives in this optimization problem. The Bekker equations are used to calculate the traction the excavator can generate for a set of rover and soil input parameters and the Baylonev equations are used to calculate the required excavation forces for a set of tool and soil input parameters [2].

To ensure the excavator can still excavate a volume of relative significance, the third objective in this problem is to maximize the scoop volume. A minimum scoop volume of $100cm^3$ is also added as a constraint. The scoop volume is a function of the blade width, blade depth, and blade length.

The fourth objective is to maximize the power efficiency of the excavator. Every motor has an optimal operational torque range that maximizes the electrical energy that is converted into mechanical energy. The power efficiency is a function of the traction generated by the motors and the radius of the wheels.

The final constraint of the system is for the pressure that the excavator exerts on the ground to overcome 10kPa. The pressure of the excavator is determined by the weight of the excavator spread across the grouser tips on all the wheels. The width of the grousers is assumed to be 3mm. This ensures that the excavator will be able to still penetrate and generate traction in a soil with a compressive strength of 10kPa.

Bounding intervals were set for each decision variable that provide a finite solution space for the problem. The input soil properties were modeled after BP-1 lunar regolith simulant and were held constant for each optimization. Three optimizations were run to find the optimal excavator in a loose, medium, and dense regolith with density and cohesion values of 1.4g/cm^3 and 300Pa, 1.7g/cm^3 and 800Pa, and 2.0g/cm^3 and 1400Pa, respectively.

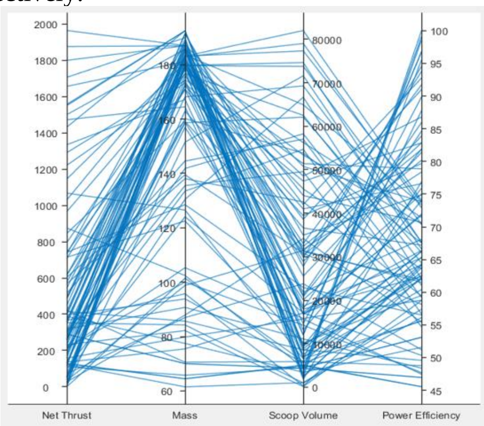

Fig 1. Set of optimal solutions in terms of objectives.

Results: The optimization function yields a 4-dimensional Pareto front of possible solutions. A parallel plot of all the possible solutions and the corresponding objective function values is shown in Figure 1. The Pareto front when just considering 3 of the 4 objectives is shown in Figure 2. These two figures illustrate the trade-offs of objectives and represent the set of dominant solutions.

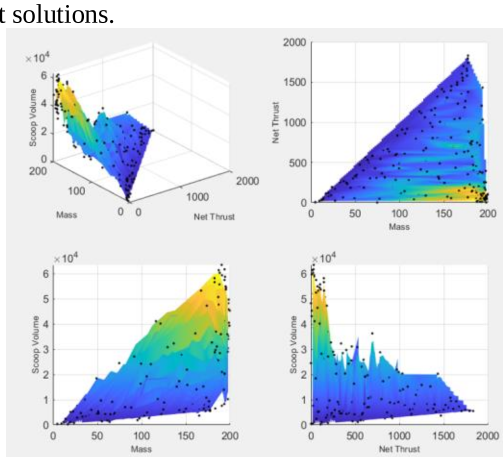

Fig 2. Pareto front of the objectives excluding power efficiency.

To yield a single optimal solution the relative importance between each objective must be established. Another method is to optimize each objective sequentially. A variety of optimal design parameters were generated in the study. A single set of results for equal weighting between all the objectives is shown in Table 3.

Table 3. Optimal design variables for equal objective weighting

Regolith	Loose	Med.	Dense
Mass (kg)	181	153	160
Wheel Diameter (cm)	50	50	50
Wheel Width (cm)	48	44	46
#Wheels	6	6	6
#Grousers Contact w Ground	3.5	3.3	3.2
Grouser Height (cm)	3	3	3
Tool Width (cm)	100	6	5
Tool Depth (cm)	5.5	1.1	1.3
Tool Side Length (cm)	70	16	16
Tool Angle (deg)	25	35	23
Tool Speed (cm/s)	10	14	17
Net Thrust (N)	187	513	629
Scoop Volume (cm^3)	38581	101	110
Power Efficiency	93	82	73

The optimization method in this study is very flexible and adaptable to varying parameters, criterium, and objective weightings. This study seeks a good formulation for optimal design of a lunar excavator in different regolith conditions and a suitable algorithm to solve it. Multiple criteria of optimization are combined linearly in the objective function to yield optimal design parameters. The results are interestingly similar for the different regolith characteristics, except the cutting tool geometry. The loose regolith requires less excavation force and thus has enabled a significantly larger tool geometry. Further refinement and tuning of the model and objective relative weighting will enable further optimization. This will enable the excavator to yield a larger scoop volume while trading off some of the excess net thrust in the denser regolith scenarios.

References: [1] Konak, Abdullah. Elsevier, *Multi-Objective Optimization Using Genetic Algorithms: A Tutorial*. [2] Wilkinson, Allen, and Alfred DeGennaro. vol. 44, Journal of Terramechanics, 2007, pp. 133–152, *Digging and Pushing Lunar Regolith: Classical Soil Mechanics and the Forces Needed for Excavation and Traction*.

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