

**INFERRING SOCIAL STRUCTURE AND DOMINANCE
RELATIONSHIPS BETWEEN RHESUS MACAQUES
USING RFID TRACKING DATA**

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Presented to
The Academic Faculty

by

Hanuma Teja Maddali

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USING RFID TRACKING DATA**

Approved by:

Professor Tucker Balch, Advisor
College of Computing
Georgia Institute of Technology

Professor Mark Clements, Co-Advisor
School of Electrical and Computer
Engineering
Georgia Institute of Technology

Professor Constantine Dovrolis
College of Computing
Georgia Institute of Technology

Professor Magnus Egerstedt
School of Electrical and Computer
Engineering
Georgia Institute of Technology

Date Approved: 4 April 2014

To my parents,

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SUMMARY

This research address the problem of inferring, through Radio-Frequency Identification (RFID) tracking data, the graph structures underlying social interactions in a group of rhesus macaques (a species of monkey). These social interactions are considered as independent affiliative and dominative components and are characterized by a variety of visual and auditory displays and gestures. Social structure in a group is an important indicator of its members' relative level of access to resources and has interesting implications for an individual's health. Automatic inference of the social structure in an animal group enables a number of important capabilities [17], including:

1. A verifiable measure of how the social structure is affected by an intervention such as a change in the environment, or the introduction of another animal, and
2. A potentially significant reduction in person hours normally used for assessing these changes.

The behaviors of interest in the context of this research are those definable using the macaques' spatial (x,y,z) position and motion inside an enclosure. Periods of time spent in close proximity with other group members are considered to be events of passive interaction and are used in the calculation of an Affiliation Matrix. This represents the strength of undirected interaction or tie-strength [9] between individual animals. Dominance is a directed relation that is quantified using a heuristic for the detection of withdrawal and displacement behaviors. The results of an analysis based on these approaches for a group of 6 male monkeys that were tracked over a period of 60 days at the Yerkes Primate Research Center are presented in this Thesis.

CHAPTER I

INTRODUCTION

Learning the social structure of a group by observing the interactions between its member agents is a valuable tool for primatologists and sociologists. The dominance relations that arise as a result of these interactions lead to changes in an agent's social environment that vary with its position in the hierarchy. [34] looks into the correlation between the stress of social hierarchy and its effects on the immune system in rhesus macaques. Dominance relations can also influence the process of learning in social groups as explored in [5]. Describing these dominance relations requires focal or group observations of the agents and a classification of behaviors based on qualitative descriptions. Traditionally, scientists must hand label either field observations or recorded data and convert this to an interaction matrix that represents some relation between different individuals. Collecting and labeling ground truth for behavioral data through manual observation is an expensive process. Another drawback is that these do not offer the option of continuous observation and consist, for example, of multiple sample of hourlong observations of visible individuals.

Most of the works described in the following chapter on related works employ manual observations for data collection from animals. A novel aspect of this research with respect to previous work on rhesus macaques is the use of Radio-Frequency Identification tags to continuously and accurately track positions of animals with a high frequency for the automated generation of social network graphs. The graphs give insight into the underlying affiliation and hierarchy in the rhesus macaque test population. Some advantages of the Radio-Frequency Identification data collection are :

1. Uninterrupted visibility of individuals.
2. Yields a large volume of data.
3. Provides a way to define social behaviors quantitatively using velocity, bearing, and proximity.

The approach to data analysis in this research uses simple histogram based techniques to aggregate behavioral events that act as strong indicators of dominance or affiliation. These are similar to the methods used by primatologists, such as the calculation of grooming matrices [29]. This work focusses on the subset of macaque behaviors that can be detected in the spatial domain. Examples of these behaviors are displacement and grooming. A detailed description of how these behaviors are quantified can be found in the Approach section of this Thesis. The results of this analysis are represented in the form of Affiliation Graphs, Heat Maps and Hierarchy Graphs. The dynamics of the social structure due to the entry and exit individuals from the group during data collection and overall stable features of this structure are also discussed.

CHAPTER II

RELATED WORK

Generation of social network graphs of animals using behavioral analysis has been a topic of interest for several decades. In primatology, the works of Toshisada Nishida and Jane Goodall [37][22] in the 1960's involved deciphering the structure of chimpanzee communities through field observations of grooming, territorial and other behaviors. Sade [27] used sociograms to visualize the grooming patterns in a free-ranging group of rhesus monkeys at Cayo Santiago, Puerto Rico [36]. [26] describes a 3 layer conceptual framework for the study of primate social networks. In this, dyadic interactions between individuals give rise to relationships. The quality, content and temporal structure of these interactions decide the nature of the relationships. The visible social structure arises from the dynamics of these relationships. Affiliation and dominance relations, represented using graphs, provide the input to a model of dyadic interactions that results in behavior captured as in position data. A schematic representation of the framework adapted for the purposes of this research is shown in figure 1.

Social Network Analysis is a tool that is increasingly being used when studying large and complex animal groups [2]. [1] uses Social Network Analysis measures like betweenness, eigenvector centrality and connectedness derived from the grooming, aggression and spatial proximity networks of a rhesus macaque group to quantify sociality. One of the indicators for social proximity is physical proximity as it can dictate the degree of interaction between individuals. [4] illustrates the derivation of social networks of white-faced capuchin monkeys using a spatial distance of 5 body lengths as a proximity threshold. [23] uses a similar measure for wild mice and

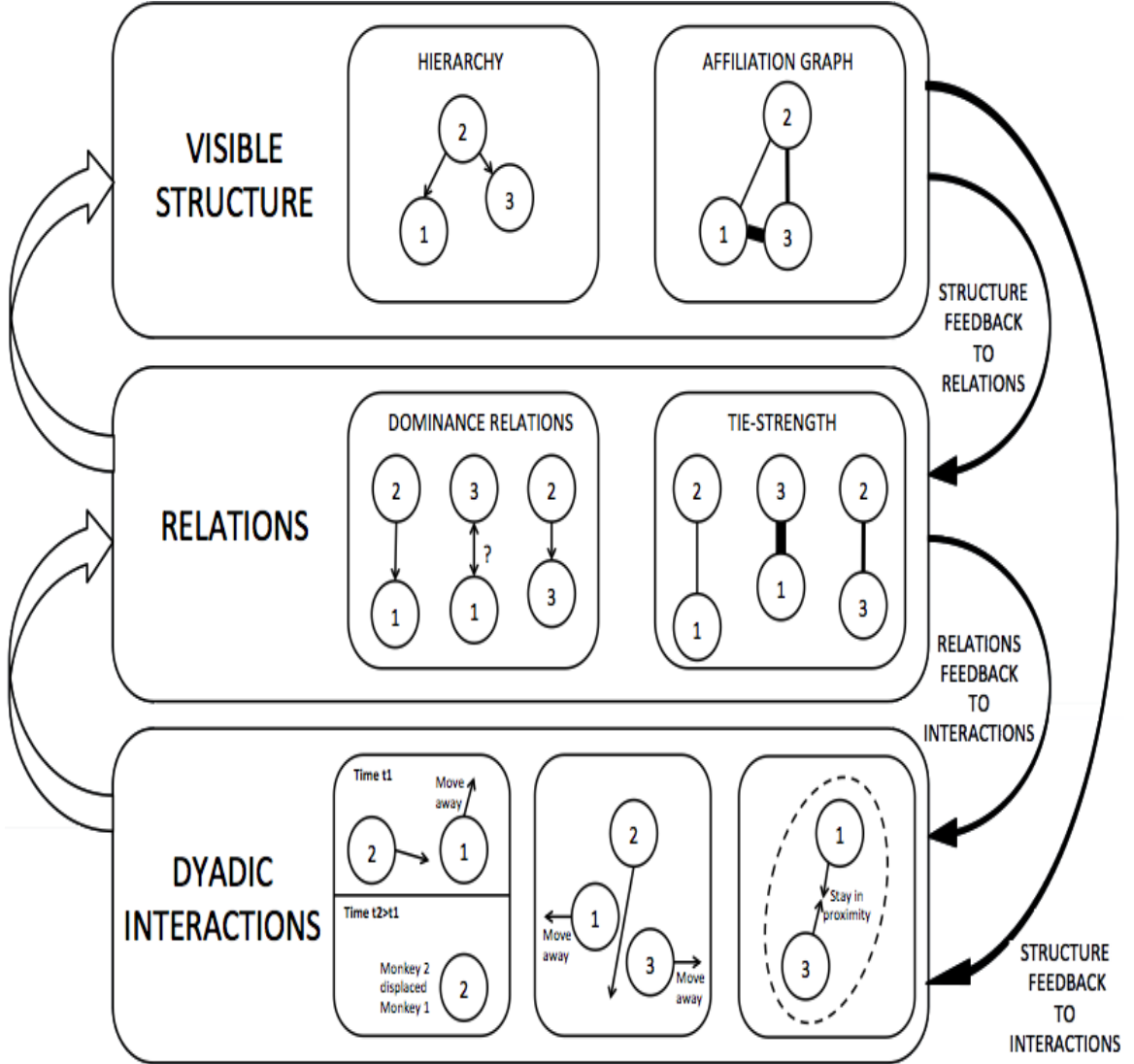


Figure 1: Hinde's 3 layer conceptual framework (adapted from [26])

Bechstein's bat colonies. Sade's work using network-based graphs in the study of nonhuman primates [29, 31, 30, 3] more specifically rhesus macaques is important in the context of this research. He uses grooming matrices graphically represented by sociograms, where each cell indicates the number of grooming events involving the row monkey and column monkey. One measure of individual importance used in [29] is the in-degree of each monkey in a sociogram that indicates the number of grooming partners.

Dominance relationships are an interesting aspect of social structure. [8] describes

the concept of a "dominance style" in macaque societies where the distribution of social power among rhesus macaques in particular is described to be uniform but hierarchical. [28] provides a summary of attack and flight behaviors as flowcharts, the components of which are continual units of behavior. The significance of the decomposition of behavior into temporal sequences is in their applications for behavior recognition and agent based models (ABM) such as in [7], DOMWORLD [10], and SMALLDOMWORLD [11]. Simulation of animals using a reasonably accurate ABM offsets the costs involved in data collection and can also be repeated with a frequency greater than for real animal subjects.

CHAPTER III

MACAQUE SOCIAL ORGANIZATION

Rhesus macaques are one of the most widely studied nonhuman primates. They live in multi-male and multi-female groups which are matrilineal. The dominance rank of an individual indicates its position in the group hierarchy. This mostly depends on the rank of its mother. Most hierarchies in rhesus macaques are strictly linear so there is a transitivity in the dominance ranks. This means that if $\text{rank}(\text{monkey } i) > \text{rank}(\text{monkey } j)$ and $\text{rank}(\text{monkey } j) > \text{rank}(\text{monkey } k)$, this implies $\text{rank}(\text{monkey } i) > \text{rank}(\text{monkey } k)$. There may be occasions with a low probability where a triadic inconsistency occurs. An established hierarchy is usually stable for several years [28].

Affiliative interactions (e.g., play, grooming, resting together) do occur fairly regularly between animals with disparate ranks. It is not necessarily the case that subordinate individuals will always avoid dominant individuals. Social grooming, is the main affiliative behavior used by rhesus macaques to establish and cement social relationships with one another [18]. A rhesus macaque can request grooming from another individual by lip smacking to encourage the other individual to approach and then by lying down in front of the other, often exposing the part of the body that needs to be groomed. Grooming can last a few seconds, minutes, or, occasionally, over an hour. The male macaques in our dataset have grooming sessions that last roughly around 2 minutes.

The group that this research considers for its test case is an all-male group of 6 macaques. This all-male group was formed in order to present them with an ecologically-relevant social challenge. Wild rhesus males typically leave their natal groups around puberty [13], and will either join a new mixed-sex group, or associate

in all-male groups for varying lengths of time. Male group membership is transient, and they typically will change groups more than once during their lifetime. The small size of the group in our dataset provides an ideal test case for analyzing macaque social structure. There is some indication that male ranks in a group like in the dataset used for this research fluctuate more than female ranks do. This is since female rank is inherited and females are in kin groups, whereas males are basically on their own [25]. However, the hierarchy in this group was well-established before the tracking was started, and has been relatively unchanged since that time

CHAPTER IV

APPROACH

The approach used in this research is the same as described in [17]. There are two main quantitative criteria assessed in order to infer the social structure; Time spent close to conspecifics, and displacements. An affiliation matrix is used to represent the total duration of events detected as passive interaction behavior between any two monkeys. This forms an undirected tie-strength (closeness of relationships) graph. A directed graph of hierarchy is constructed by using the well cited assumption of a linear hierarchy for rhesus macaques [1][18]. Events that contribute to the adjacency matrix for this graph are withdrawals or displacements where a lower ranked monkey moves away from a higher ranked monkey. Displacements are one of the observable behaviors that can act as a strong indication of tie-strength and dominance. To quantify the directedness of interaction during these events we construct histograms of the dot products of motion orientation and relative position. This gives us a measure of how much time a monkey spends in moving towards or away from other group members.

4.1 Inferring tie-strength

A necessary prerequisite for most types of interaction between individuals is spatial proximity. Individuals cannot cooperate if they are not close enough to perceive that their assistance is needed or desired and to provide said service within an appropriate time frame [4]. We measure tie-strength by detecting events of passive interaction. Tie-strength for monkeys i and j is the time spent per day engaging in events such as grooming or passive interaction. Grooming events are characterized by 2 stationary monkeys within a threshold distance of d_{thr} and a duration of at least t_{thr} (time

threshold). This data gives us an affiliation matrix A for the social network of the monkeys where each element $[A]_{ij}$ of the matrix represents the tie-strength between monkeys i and j . The Affiliation matrix is symmetric ($[A]_{ij} = [A]_{ji}$) as the passive interaction events are considered to be undirected. Figure 2 shows the Affiliation graph representing matrix A . A threshold has been applied on the edges to emphasize strong ties. An estimate of the sociability of an individual can be derived from the weighted degree of each node. The greater the weighted degree, the more that monkey interacts with the others in the group. We see that Monkey 6 and Monkey 2 are an example of a pair that does not interact frequently. This can also be visualized using Heat Maps as shown in Figure 3. We can clearly see that the region of the enclosure frequented by Monkey 2 (indicated by bright yellow) does not overlap with that of Monkeys 5 or 6. Whereas Monkeys 5 and 6 have strongly overlapping regions and, from Figure 2, strong affiliation.

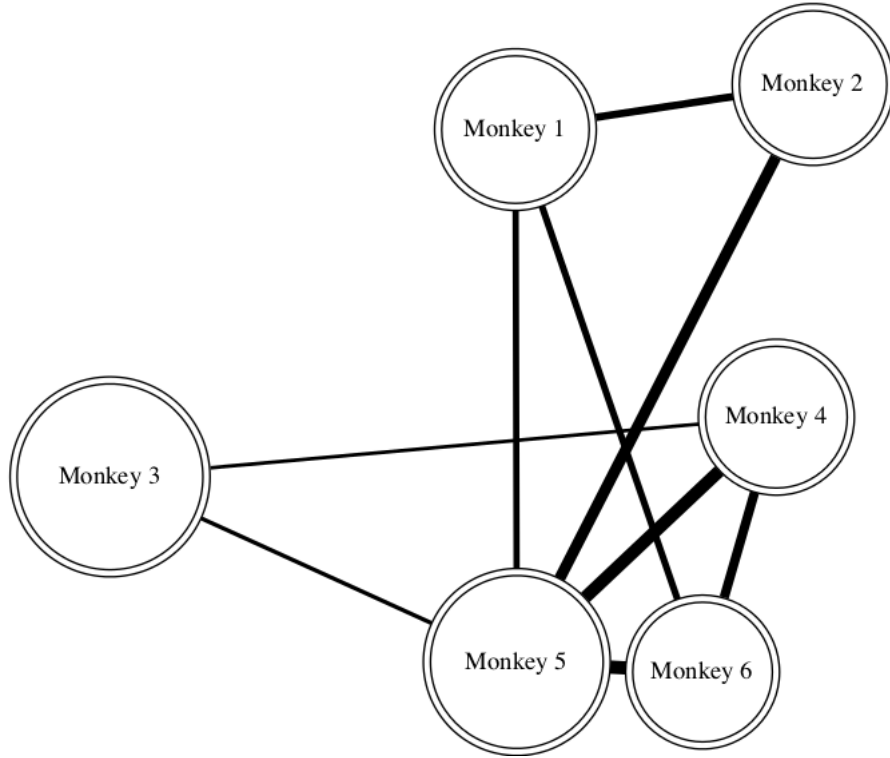


Figure 2: An example thresholded Undirected Affiliation Graph

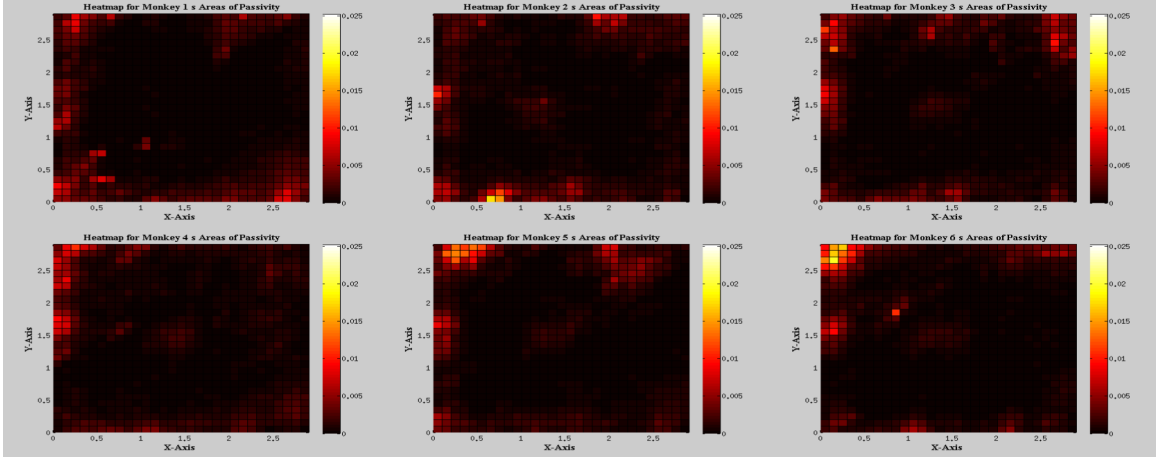


Figure 3: Examples of individual Heat Maps for the monkeys over the area of the enclosure. Brighter areas indicate regions of the enclosure where monkeys remain stationary with greater frequency.

4.2 Inferring dominance relations

After dominance relations have been established between the agents a subordinate individual will usually avoid the dominant one or express fear and submission in his presence [18]. Interactive behaviors between monkeys can be inferred by detecting individual behaviors that act as strong indicators of dominance. Some behaviors that can be ascertained using position and velocity data include withdrawals, displacements, attacking and chasing. For example, if two monkeys are detected to be running while within proximity of each other there is a high probability this is a chasing behavior. Dominance information may then be extracted from all the interactive behaviors detected as chasing.

Withdrawal is characterized by a lower ranking individual A changing its trajectory with a slightly higher exit velocity to allow a higher ranking individual B to continue unimpeded. Withdrawals involve one animal actively avoiding another. There is no distance implied, so it can involve moving out of the way when another animal approaches, or it can mean trying to get out of another animal’s line of sight from across the way. It is usually very obvious that the lower-ranking animal is aware

of the presence or movements of the higher-ranking animal and adjusts their behavior accordingly. Displacement is similar to withdrawal except that the lower ranking individual A is initially stationary, for example, near a feeding area. The arrival of higher ranking individual B can cause A to exit the feeding area hastily to allow B to physically occupy the place of the lower ranking animal. Here B displaces A, it is as though A gave up his seat to B. So displacement involves one animal literally taking the place of another. Attacking could be inferred from an initial sudden rise in velocity of an individual A in the direction of another individual B. But this can also be classified as chase play rather than aggressive behavior and is ambiguous. These behaviors can then be combined to recover the directed graph representing the social network of the animals.

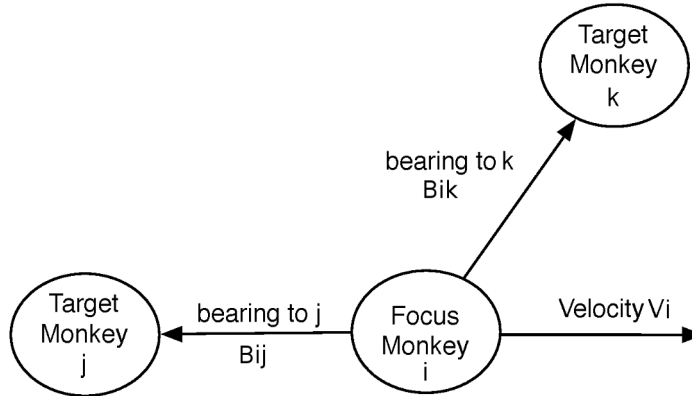


Figure 4: Relative direction of travel is determined by calculating the velocity of the focus monkey. Then the bearing from the focus monkey i to any target monkey j or k within a distance threshold is computed. The dot product between the focus monkey i 's velocity and bearing to each neighbor determines its relative motion.

Currently we quantify the dominance relationship TA_{ij} using displacements and withdrawals between monkeys i and j . If $TA_{ij} > TA_{ji}$ then monkey j dominates monkey i . To obtain TA_{ij} we calculate the bearing B_{ij} of monkey i to monkey j and i 's velocity as V_i . For example, in figure 4 the dot product between the focus monkey i 's velocity V_i and its bearing B_{ij} to target monkey j will be -1 as it is moving directly away. DV_{ij} is the component of monkey i 's motion directed towards monkey j . It is

given by the magnitude of the projection of V_i onto the unit vector B_{ij} .

$$DV_{ij} = V_i \cdot B_{ij} \quad (1)$$

DV_{ij} is a measure of monkey i 's motion with respect to monkey j , a value in $[-1, 1]$. Negative values of DV_{ij} indicate monkey i is moving away from monkey j whereas positive values indicate monkey i is moving towards monkey j . Our events of interest are when $-1 \leq DV_{ij} \leq dp_{thr}$ i.e. monkey i is moving directly away or at a slight angle from monkey j and dp_{thr} is a threshold on the dot product. TA_{ij} is the total number of all events where $-1 \leq DV_{ij} \leq dp_{thr}$ and where either monkey i or monkey j is stationary. If monkey j is non stationary then it must have a speed $abs(V_j) \geq dsp_{thr}$. The hierarchy Matrix H is given by

$$[H]_{ij} = \begin{cases} 1 & \text{if } TA_{ij} < TA_{ji} \text{ (} j \text{ dominates } i \text{ because } i \text{ moves away from } j \text{ more often)}; \\ 0 & \text{if } TA_{ij} \geq TA_{ji} \text{ (} i \text{ dominates } j \text{)}. \end{cases} \quad (2)$$

A value of zero for $[H]_{ij}$ may also indicate lack of data that can quantify the dominance relation. See Figure 5 for the directed acyclic Hierarchy graph derived from matrix H . The ordering of the nodes of the graph is based on the out-degree of the monkey. The out-degree of monkey i is the number of monkeys dominated by monkey i . Thus, the alpha monkey is the monkey with the highest out-degree while the lowest monkey in the graph has an out-degree of zero as it dominates no monkey. Directed edges are then inserted from monkey i to monkey j based on a one in the Hierarchy Matrix at location i,j .

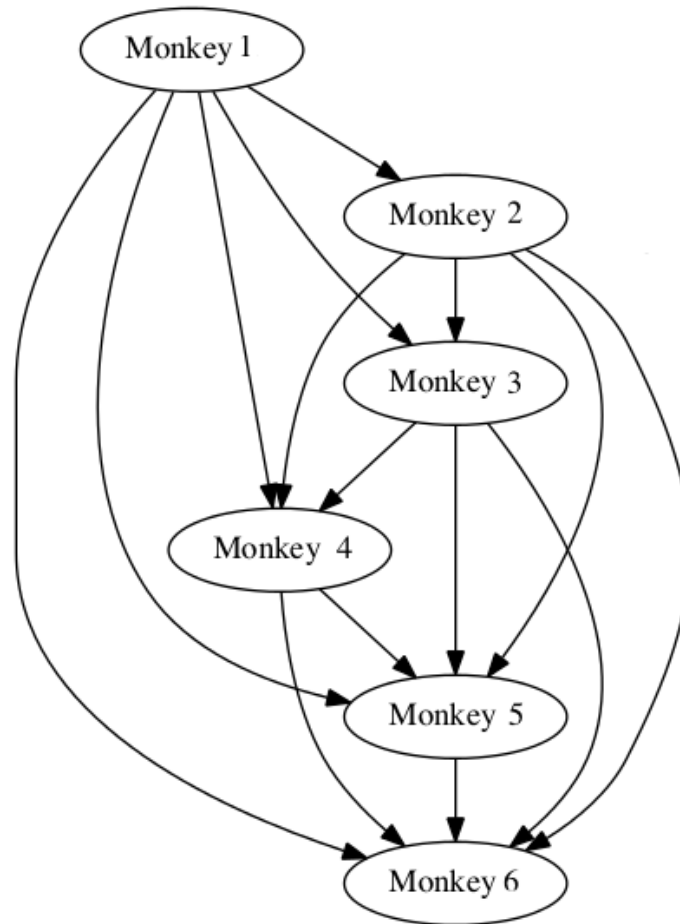


Figure 5: An example Directed Hierarchy Graph. The presence of an edge from Monkey i to Monkey j indicates that Monkey i dominates Monkey j .

CHAPTER V

RESULTS IN SIMULATION

The material in this chapter is drawn from a paper [11] led by my colleague Brian Hrotenok, for which I am a contributing author. The results in this chapter were derived using a simulated monkey behavior model developed by Brian with inputs from primatologists at Yerkes Primate Research Center. The algorithms and code I developed were used to assess and classify that behaviour.

The objective of this Thesis is to infer social structure from the tracking dataset for a single group of macaques. This presents the drawback of having a single test case with which to verify the approach discussed thus far. The advantage of using simulated behavior models becomes apparent in this situation. In [11] we have used an agent based model `SMALLDOMWORLD` to generate test data from simulated macaques (See figure 6). This gives an opportunity to analyse the expected performance when we cannot access the ground truth.

The model is a modification of [10] for the small and continuous environment in our dataset where monkeys frequently interact with the enclosure. The behavior of the individuals is guided by three components: a grouping component that draws individuals together, a dominance component where individuals confront each other and the winner chases the loser, and a random component where individuals wander about their environment at low speed. The dominance relations for the simulated macaques are established and are not updated after every encounter as in `DOMWORLD`. Dominance encounters occur only within an individual is within a personal distance threshold of another. The probability of an intrusion on personal space resulting in a dominance encounter is given by the parameter σ where $\sigma = 1.0$ indicates

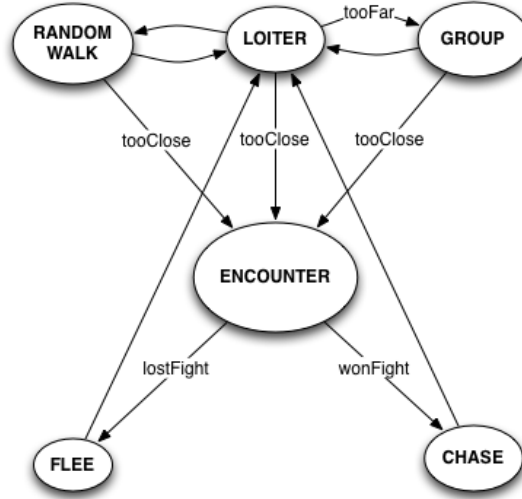


Figure 6: The SMALLDOMWORLD agent based model for rhesus macaques [11]

a completely stable dominance structure with no confrontations, and $\sigma = 0.0$ ensures that any intrusion results in a confrontation. The grouping component manifests itself in the tendency of individuals to remain within some proximity of other group members. A monkey far away from the center of its group selects another visible monkey using association preference matrix P , where $[P]_{ij}$ is the association preference of monkey j with respect to monkey i .

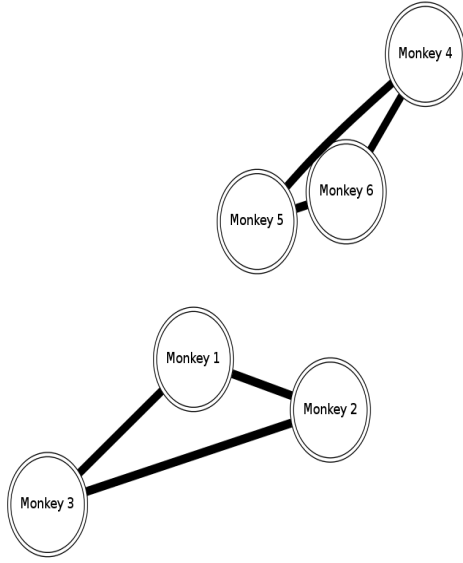
Table 1: Simulation parameters used for experiments

Personal distance	0.25m
Near distance	0.8m
Fleeing speed	2.0m/s
Chasing speed	1.0m/s
Grouping speed	0.25m/s
Wander speed	0.12m/s

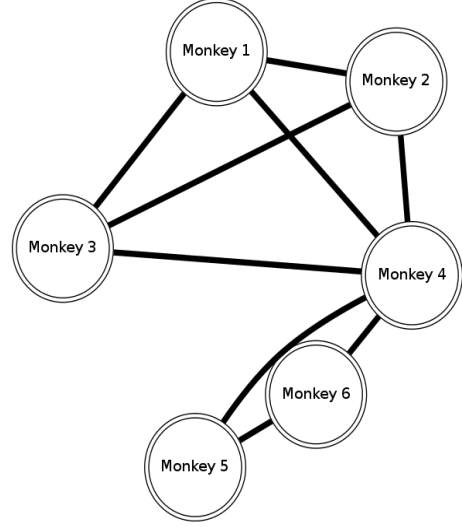
Three cases were considered with the data collected from the textsSmallDomWorld model. The dominance relations are assumed to be linear are kept the same for all cases. This is represented by figure 7(c). A monkey i that is immediately above monkey j in the hierarchy has a dominance weight that is twice that of monkey j .

Hierarchy stability $\sigma = 0.8$ such that the frequency of dominance interactions is not too high and doesn't overwhelm affiliative interaction.

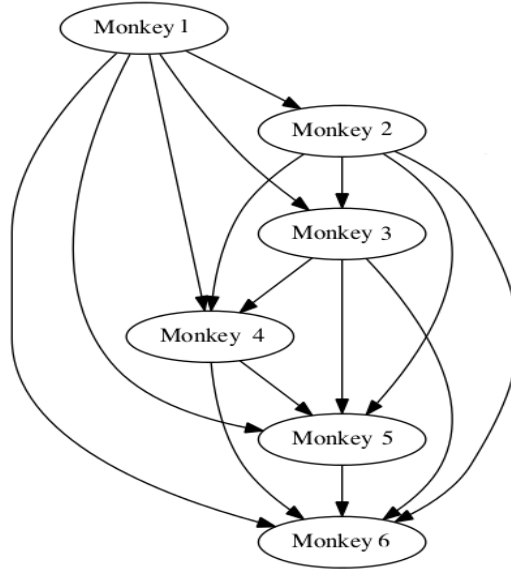
1. Case 1: There are two disconnected subgroups with respect to the association preference matrix P represented by figure 7(a). Monkeys 1, 2, and 3 form the first clique and monkeys 4, 5, and 6 form the second clique. P_{ij} is 1.0 if i and j belong to the same subgroup and 0.0 if not.
2. Case 2: Monkey 4 acts as a hinge node between the subgroups. The hinge node h has equal preference for either subgroup ($P_{hj} = 1.0, \forall j$) but isn't preferred by other nodes ($P_{ih} = 0.0, \forall i$). This is shown in figure 7(b).
3. Case 3: The association preference matrix is same as in Case 2. except that other individuals are also allowed to preferentially associate ($P_{ih} = 1.0, \forall i$) with monkey 4, the hinge node in figure 7(b). This case is interesting as it allows for scenarios where recovered association preferences may not be accurate. If we have monkey i and monkey j with a high preference for monkey k , then we can expect that our affiliation metric may also represent monkeys i and j have a sizable preference simply because they spend time in the company of monkey k . This kind of triadic closure property may or may not hold true.



(a) Ground truth association preference for simulation case 1

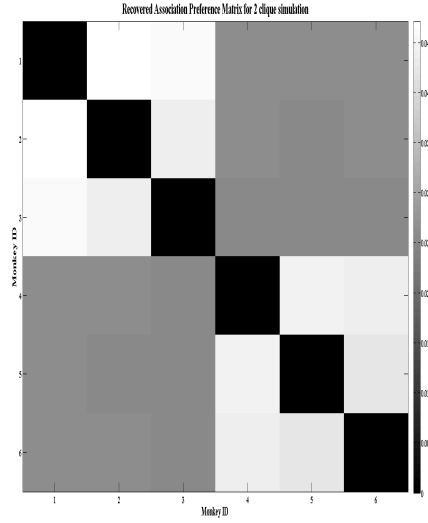


(b) Ground truth association preference for simulation cases 2 and 3

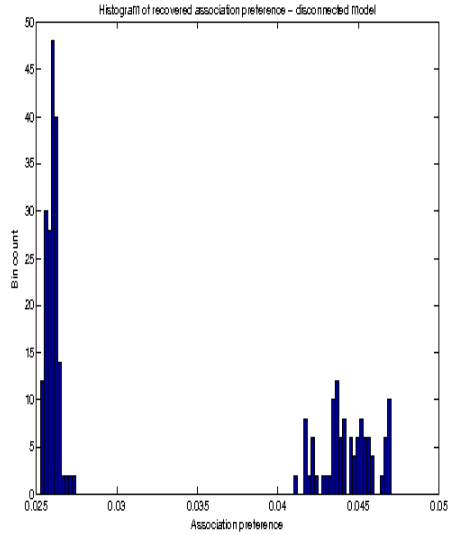


(c) Ground truth Hierarchy Graph for all three cases of simulation

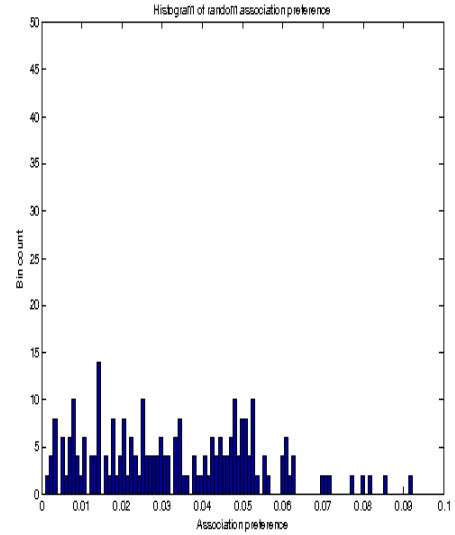
Figure 7: Ground truth for simulation experiments



(a) Association preference values recovered from simulations for case 1

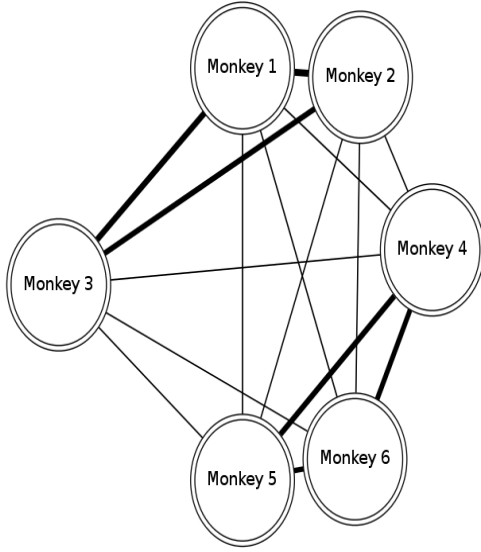


(b) Histogram of association preference values recovered from the 2 clique scenario of case 1. The values form a clear bimodal distribution

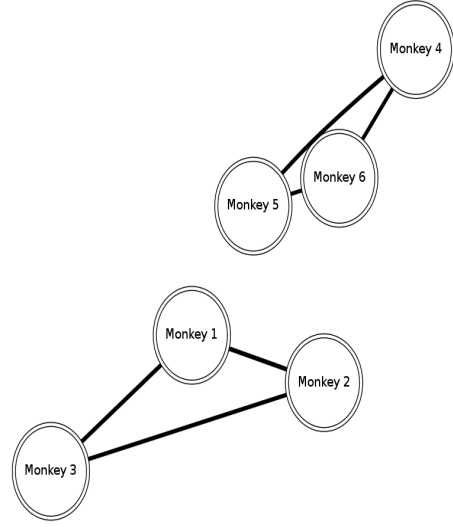


(c) Histogram of association preference values recovered from randomly generated association preference

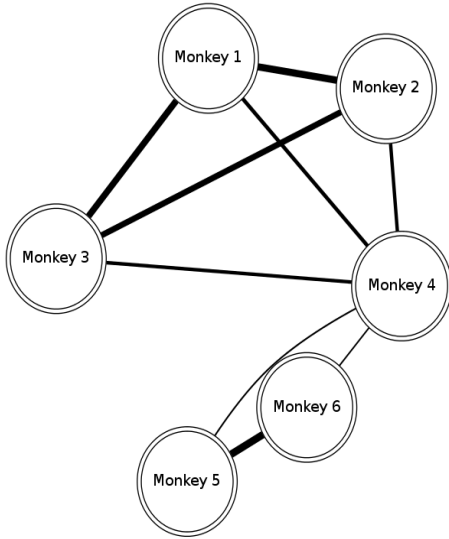
Figure 8: Association preference distribution used to obtain edge weight threshold



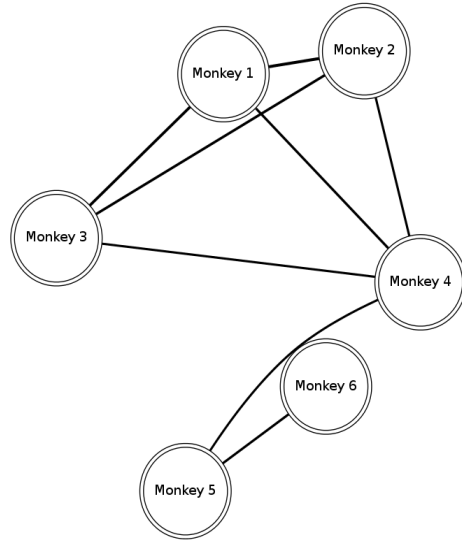
(a) Graph representation of P inferred from simulations for case 1



(b) Graph representation of P inferred from simulations after applying threshold τ for case 1



(c) Graph representation of P inferred from simulations after applying threshold τ for case 2



(d) Graph representation of P inferred from simulations after applying threshold τ for case 3

Figure 9: Recovered structure

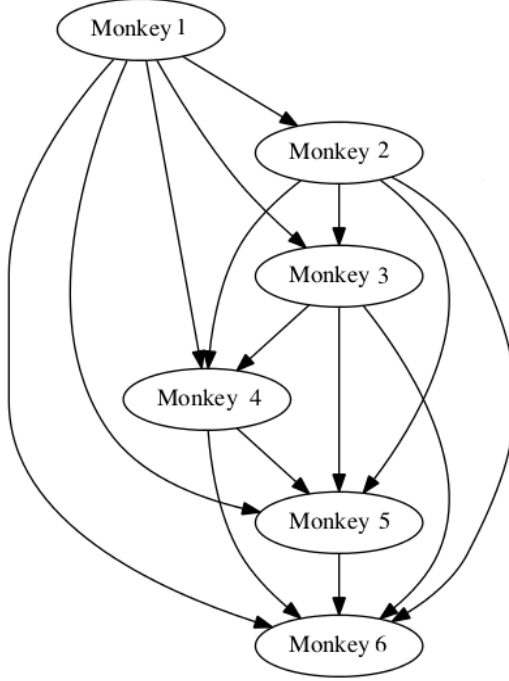


Figure 10: Inferred Hierarchy Graph in all three cases of simulation

The error metric used to compare ground truth preference matrices with the recovered matrices is the Frobenius norm. To provide a baseline, the results for the association preferences assigned according to cases 1, 2, and 3 are also compared with simulations initialized with randomly generated association preference matrices but with the same structures (row-normalized, zero diagonal, symmetric). This is shown in table 2.

In order to recover the graph structures in figure 9 the values of the inferred P matrix are thresholded by a value τ . Figures 8(c), and 8(b) shows the distribution of the values of association preference matrix P . We see that weak links between monkeys from different groups and strong intra-group associations form a bimodal distribution with a clear separation between them for Case 1 with two subgroups.

$$\tau = \frac{1}{n^2} \sum_{i,j} P_{ij}$$

where n is the number of agents, worked reliably for all the cases 1, 2, and 3.

For cases 1 and 2, the approach discussed in this Thesis enables successful and consistent recovery of the dominance relationships without error. This is observed by comparing ground truth in figure 7 with inferred hierarchy in figure 10. The recovered association preferences that are significantly closer to ground truth than a random preference. This can be seen by comparing the ground truth in figure 7 with inferred association preference in figure 9. Case 3 understandably shows a relatively degraded performance.

Table 2: Frobenious error of recovered association preference as compared to a randomly generated symmetric, normalized matrix with zero diagonal. Averaged over 10 runs.

Recovered Association Preference	Avg. error (std.)	Random Association Preference
disconnected	0.1744 (0.0014)	0.2408 (0.0326)
neutral hinge	0.1002 (0.0015)	0.1797 (0.0350)
preferred hinge	0.1388 (0.0004)	0.1869 (0.0158)

CHAPTER VI

RESULTS WITH LIVE ANIMALS

The tracking experiments were carried out over a period of 60 continuous days in a metal enclosure (3 m by 3 m) at Yerkes National Primate Research Center - Emory University, Georgia. This work presents the results obtained from analyzing the data from the first 36 days. The enclosure houses six male monkeys each with a collar that has four tags associated with it, see figure 11.

Table 3: Macaque group details

Average crown-rump length	50.29 ± 1.99 cm (Taken as 1 body length)
Average age	4.5 years

A Ubisense 7000 Real Time Location System was setup outside the enclosure similar to the arrangement described in [12]. The outdoor setting was challenging, with varying weather conditions (temperature, wind), increased possibility of Radio Frequency interference.

The commercial Radio-Frequency Identification location system is set up around the workspace/arena for our experiments, as seen in fig. 12. The sensors were positioned on the posts embedded around the enclosure. Each sensor is interfaced with a server that logs tag location data.

6.1 Data Collection and Filtering

The RTLS system consists of a set of eight RF signal receivers (sensors), which are arranged around the volume of interest. The eight sensors are connected by a daisy chain of Ethernet connections to a server that runs Ubisense proprietary software that computes and logs tag positions, as seen in figure 13.



(a) Collar with Radio-Frequency Identification tags



(b) Monkey Wearing a Collar

Figure 11: Tracking Collars: As seen in (a), the collars for the monkeys are machined plastic with four Radio-Frequency Identification tags each.

Tags in the arena intermittently and asynchronously emit radio frequency signals (at near regular intervals) which are then triangulated by the Ubisense software for a position estimate. In our experiments, each tag had an update frequency of about 1.25 Hz. Readings are lost when the sensed signal is not strong enough. In addition to random noise, the tag position estimates are also affected by occlusions. This can be an issue especially when subjects (monkeys or people) interact. One part of our strategy for reducing error is to equip each target with four tags, and to use a filtering and averaging strategy to infer more accurate pose information. The Ubisense system provides tag-id, 3D position tuple outputs. This data is aggregated for each tag and is utilized by a smoothing filter to estimate primate (collar) positions. In the smoothing filter removal of outliers is performed using a median filter. As readings from different tags are unlikely to have coinciding timestamps, we synchronize the readings of the (four) associated tags for each collar such that each of them has position estimates at time instances coincident with a constant rate of 30 Hz. Since the duration between consecutive readings (for a given tag) are quite short, standard linear interpolation is used. For each collar, the filter smooths out and averages tag readings for each

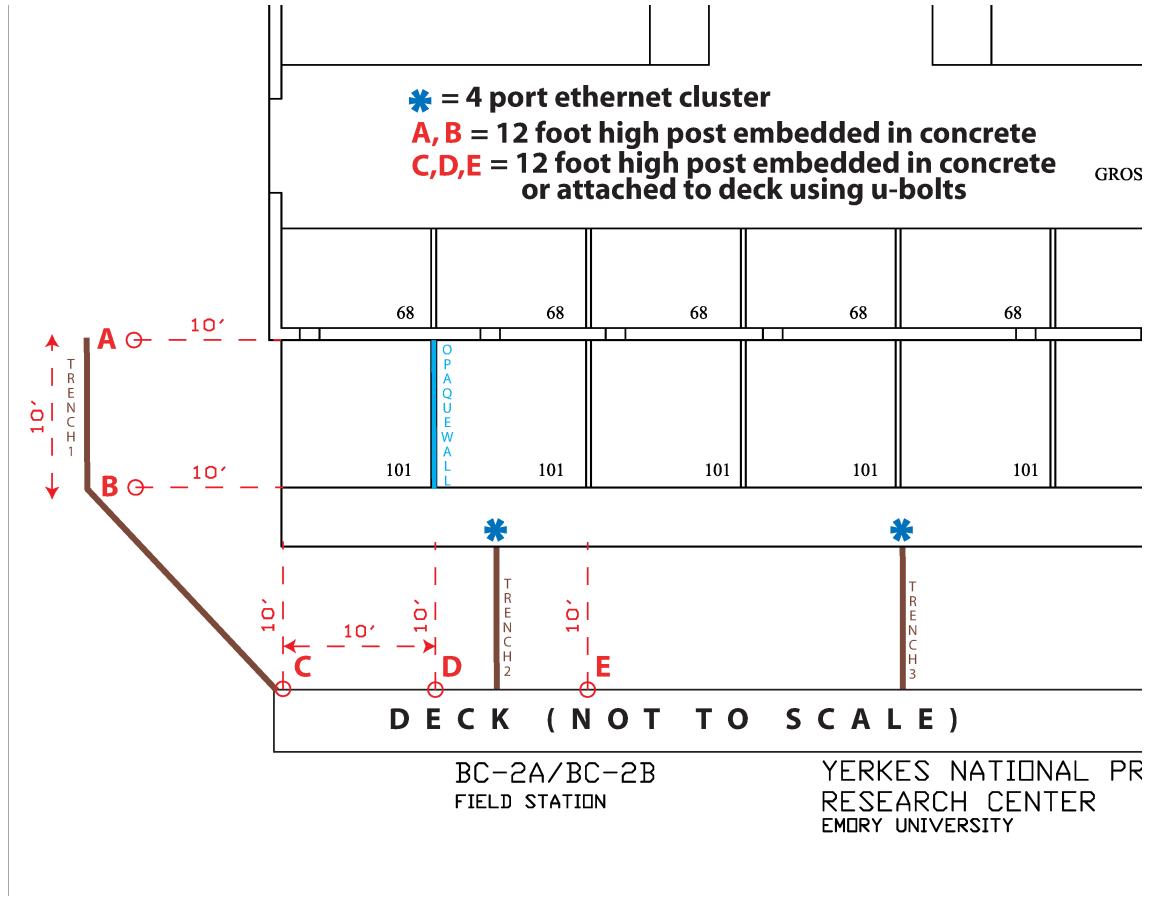


Figure 12: Enclosure floor plan and sensor placement. Each 10ft by 10ft square is an enclosure

collar to get a better estimate of ground truth. It should be noted that the use of Radio-Frequency Identification bypasses the problem of data association altogether. Tag to collar associations are known a priori, and allow for unambiguous collar-wise filtering. All signal processing was done using Matlab R2012a (7.14.0.738).

As mentioned previously, the data was collected over a period of 60 days. Figure 14 shows a tag-wise histogram of number of samples obtained over the period of data collection. Increasing redness indicates increasing number of samples collected on that day. The tags are grouped according to their corresponding collars (4 tags per collar) and hence the corresponding monkey. The data from the first 36 days (between June 5, 2014 and July 10, 2014) and divided that into 3 periods

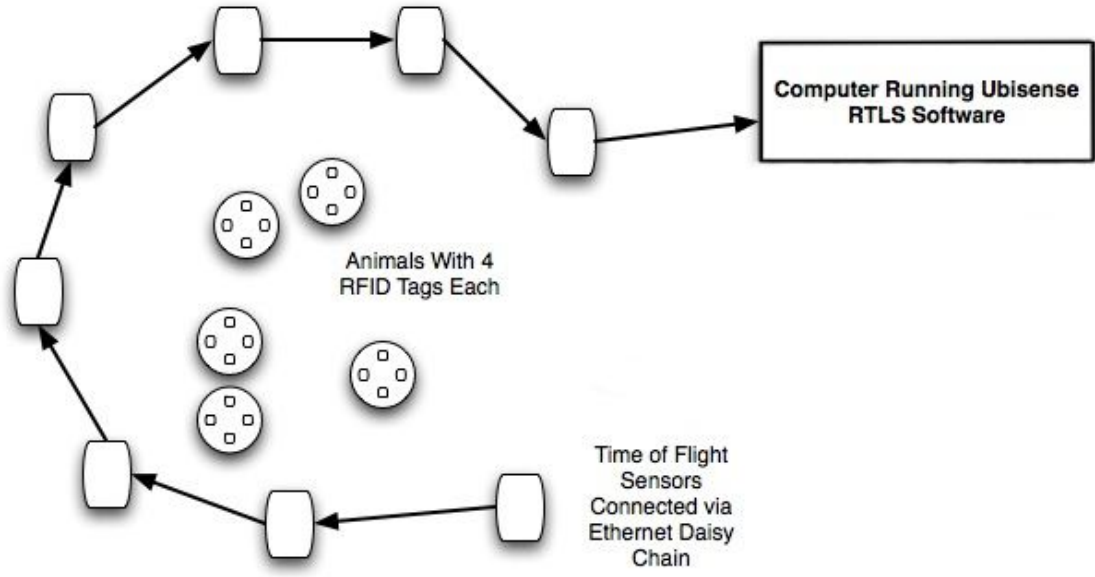


Figure 13: Tracking System System Representation

1. Period 1 (Days 1 to 9): Tracking data is available for all monkeys in this period.
2. Period 2 (Days 10 to 28): Monkey 1 removed from enclosure. Data available for monkeys 2, 3, 4, 5, and 6 in this period.
3. Period 3 (Days 29 to 36) : Monkey 4 data unavailable due to non-functioning tags. Data available for monkeys 1, 2, 3, 5, and 6 in this period.

The analysis with respect to inferring the tie-strength, heat maps and dominance relations is first performed independently for the three periods and then over all 36 days. Our plotting tools are Matlab R2012a (7.14.0.738) and an open source software called Graphviz. Graphviz is powerful and descriptive because it allows us to use information gathered from relevant matrices to place nodes and edges in specific ways.

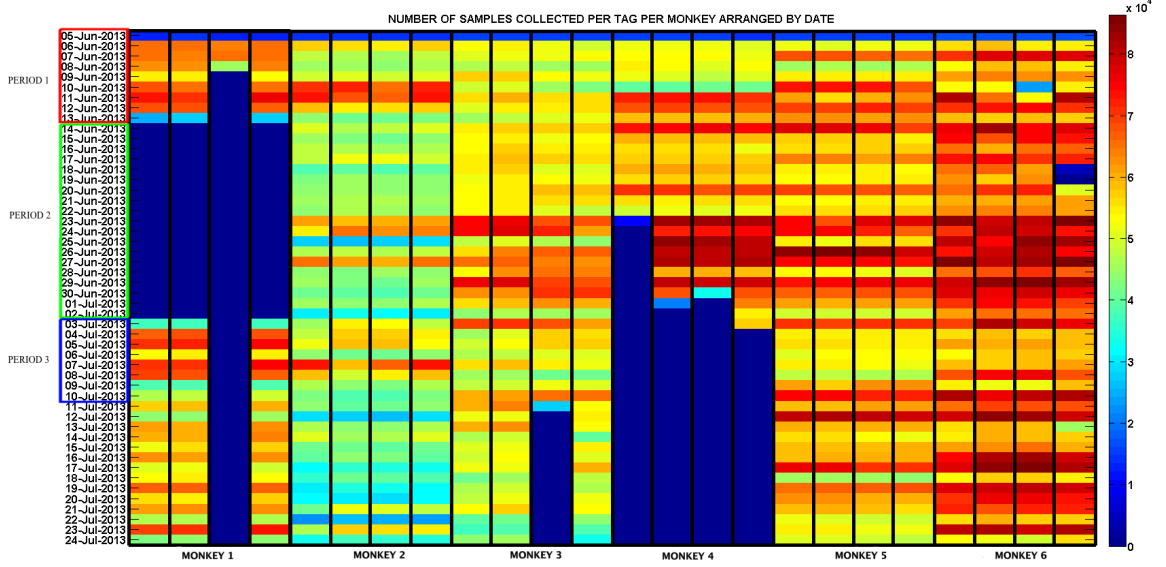


Figure 14: Tag-wise histogram of sample collection between June 5, 2014 and July 24, 2014 grouped by the corresponding monkeys

6.2 Tie-Strength

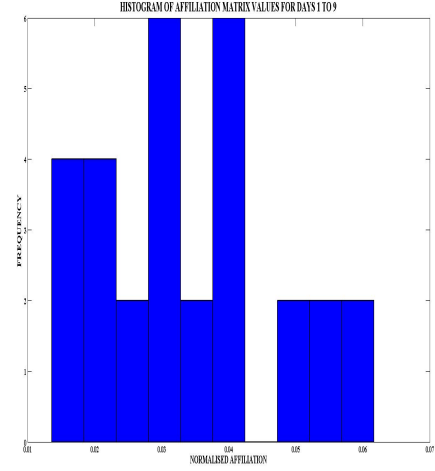
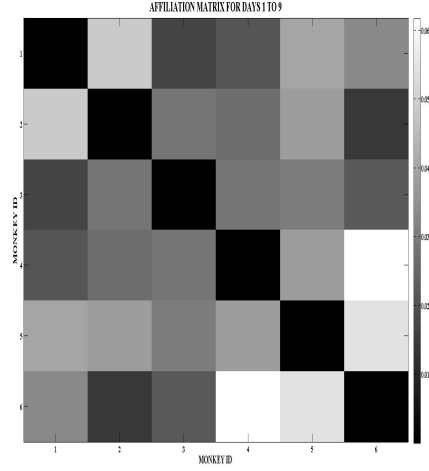
6.2.1 Affiliation Graphs

The graphs in figures 15,16, and 17 illustrate the affiliation graphs for the monkeys in each period of the 36 days. Each node represents a particular monkey. The thickness of the edge (the edge weight) between monkey i and monkey j is proportional to the value of the affiliation matrix element $[A]_{ij}$. The value of $[A]_{ij}$ is calculated using the time spent by monkeys i and j on passive interaction events of duration greater than or equal to $t_{thr} = 2$ minutes (Average length of a grooming session for the group under consideration). During this time both monkeys i and j should be within a threshold distance $d_{thr} = 0.8$ m from each other (1.6 body lengths for a rhesus macaque) and both of them must be stationary. The speed threshold below which the monkey is assumed stationary is 0.1m/s (median speed of the monkeys over the entire dataset). An estimate of the sociability of an individual, however, can be derived from the weighted degree of each node. The more the weighted degree, the more that monkey interacts with the others in the group. Rather than retaining all the edges a threshold

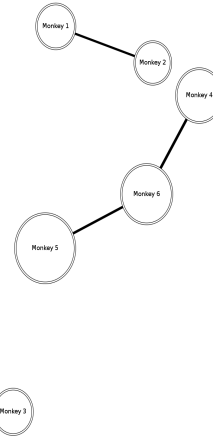
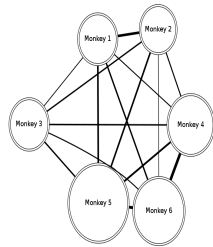
is applied to emphasize strong links over weak ones. This threshold is derived from the histogram of the values in the affiliation matrix, see figures 15(b), 16(b), and 17(b). The edge weight threshold is chosen to be a value that separates the means of a bimodal approximation of the histogram. We have the following observations:

1. Period 1 (Days 1 to 9): All monkeys are present during this period. After applying the edge weight threshold of 0.045 we obtain a disconnected graph with a dyad composed of monkeys 1 and 2, a triad composed of monkeys 4, 5 and 6 and a disconnected node monkey 3. This is seen in figure 15(d).
2. Period 2 (Days 10 to 28): After applying the edge weight threshold of 0.045 we obtain a disconnected graph given by figure 16(d). Monkeys 3, 4, 5, and 6 form a clique while monkey 2 is disconnected from the group. Monkey 1 is absent and isn't considered during this period.
3. Period 3 (Days 29 to 36) : After applying the edge weight threshold of 0.06 we again obtain a disconnected graph given by figure 17(d). The Affiliation graph has two dyads, the first one is composed of monkeys 1 and 2 and the other is composed of monkeys 5 and 6. Monkey 3 is disconnected from the group. Monkey 4 is not considered in this analysis.

There are recurring elements in the Affiliation graphs over time and with the entry and exit of monkeys from the group. Monkeys 1 and 2 have a strong tie throughout the period of 36 days. This is also the case for monkeys 5 and 6 as well as monkeys 3 and 4. Monkey 3 is more likely to join the group that also includes of monkey 4. These observations are reflected in the overall Affiliation Graph in figure 18(c). Monkey 2 acts as a bridge between monkey 1 and the rest of the group.

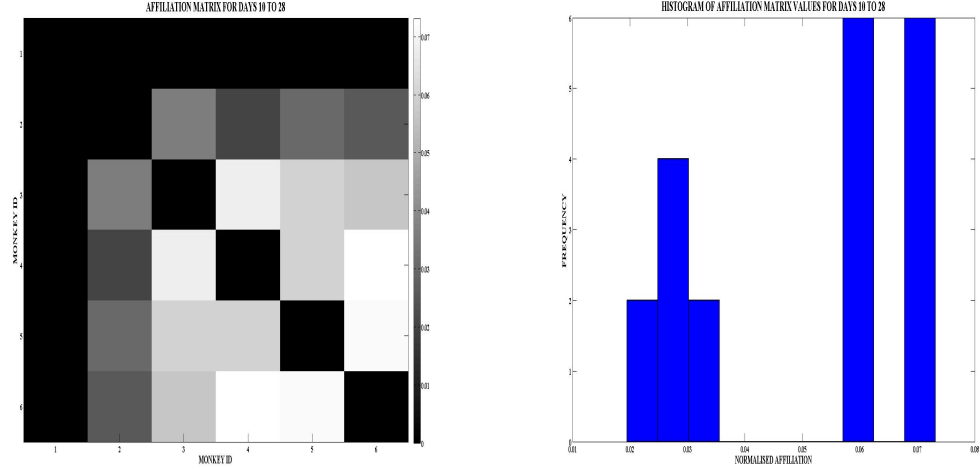


(a) Normalized Affiliation Matrix A for period 1 (b) Histogram of values in the affiliation matrix. Threshold for edges chosen at 0.045

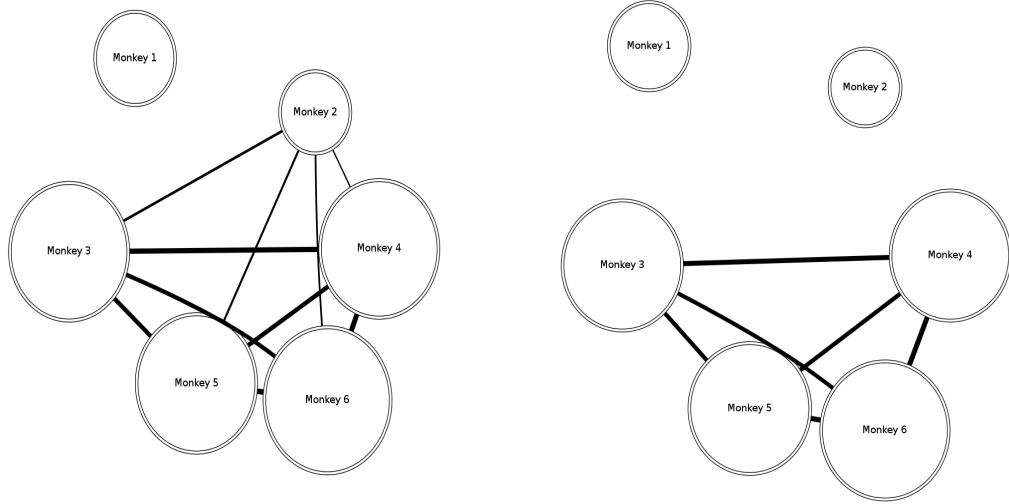


(c) Unthresholded Affiliation Graph for period 1 (d) Affiliation Graph for period 1 after applying the edge threshold of 0.045 to emphasize strong links

Figure 15: Inferred Affiliation data for Period 1 (All monkeys present in enclosure)

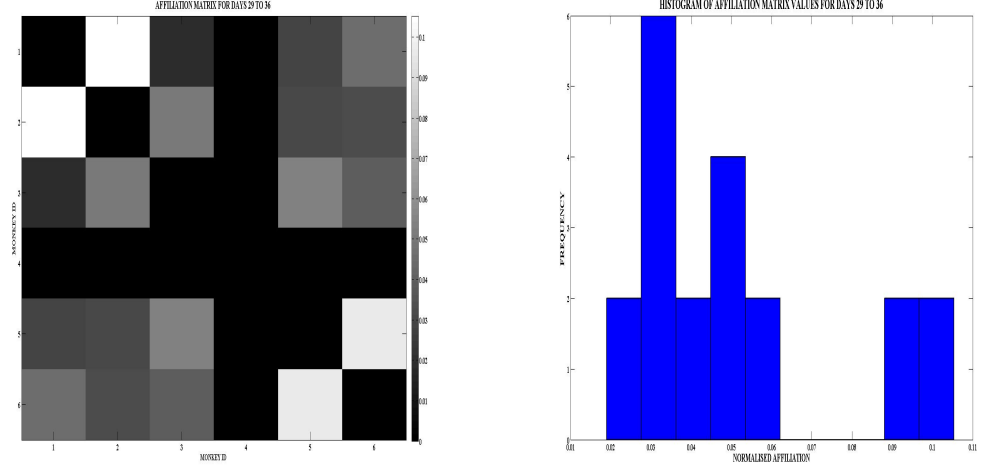


(a) Normalised Affiliation Matrix A for period 2 (b) Histogram of values in the affiliation matrix. Threshold for edges chosen at 0.045

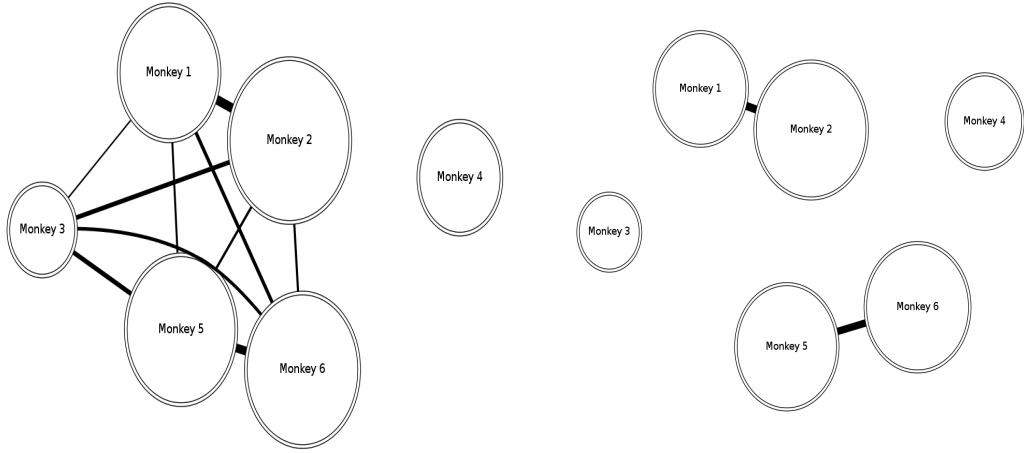


(c) Unthresholded Affiliation Graph for period 2 (d) Affiliation Graph for period 2 after applying the edge threshold of 0.045 to emphasize strong links

Figure 16: Inferred Affiliation data for Period 2 (Monkey 1's data unavailable)

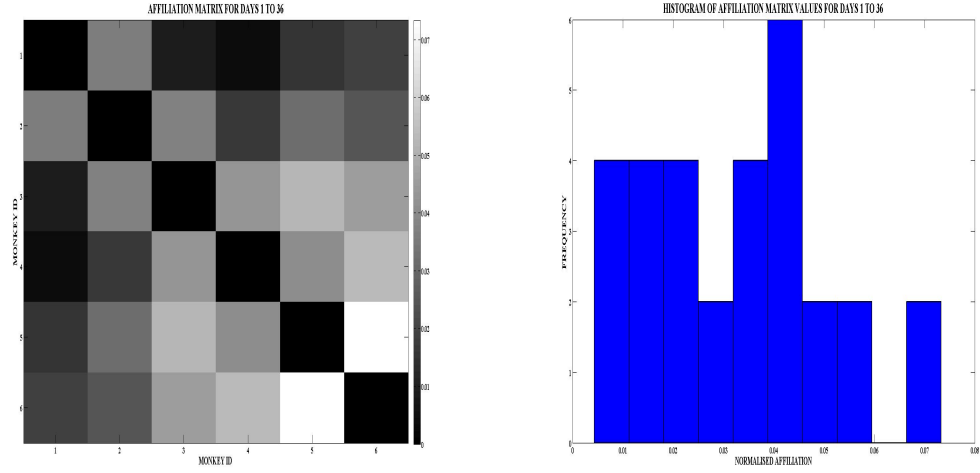


(a) Normalized Affiliation Matrix A for period 3 (b) Histogram of values in the affiliation matrix. Threshold for edges chosen at 0.045

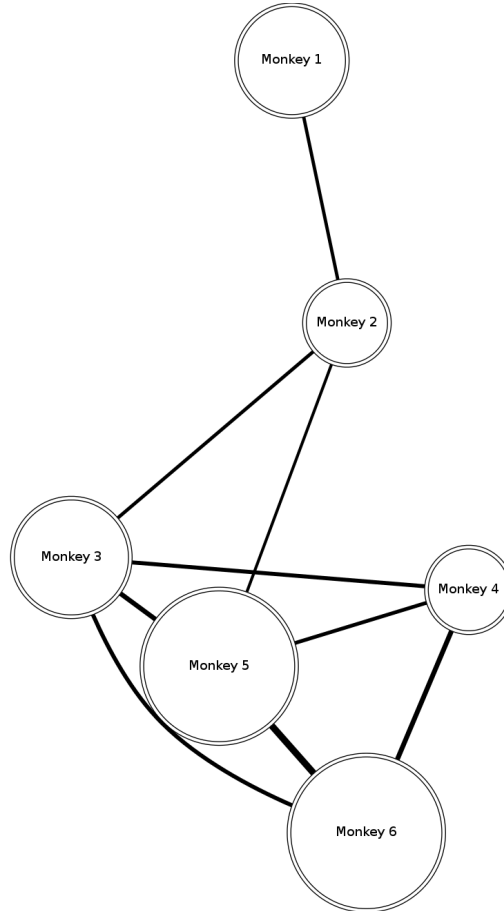


(c) Unthresholded Affiliation Graph for period 3 (d) Affiliation Graph for period 3 after applying the edge threshold of 0.06 to emphasize strong links

Figure 17: Inferred Affiliation data for Period 3 (Monkey 4's data unavailable)



(a) Normalized overall Affiliation Matrix A (b) Histogram of values in the affiliation matrix. Threshold for edges chosen at 0.0285



(c) Overall Affiliation Graph after applying the edge threshold of 0.0285 to emphasize strong links

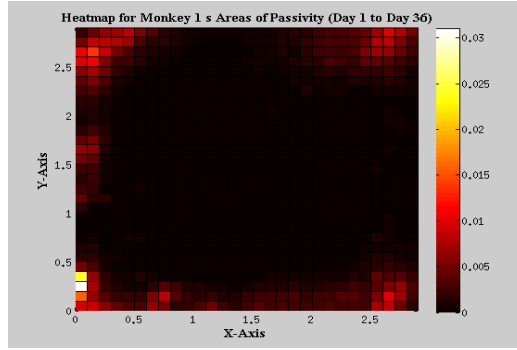
Figure 18: Inferred overall Affiliation data

6.2.2 Heat Maps

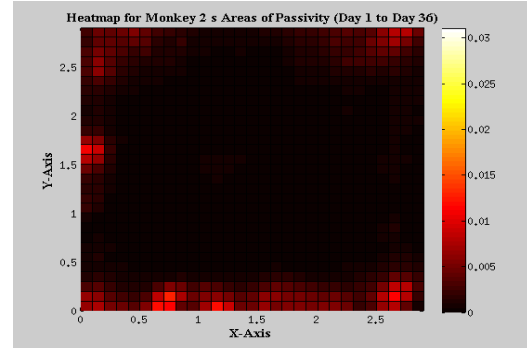
Heat Maps provide an alternate method of visualization for the information represented by Affiliation Graphs. Figure 19 was generated using position data for each monkey on all 36 days with (10 cm by 10 cm) bins over the (3 m by 3 m) enclosure. Position data associated with a speed less than a speed threshold $sp_{thr} = 0.1m/s$ is used to calculate the Heat Map histograms. They illustrate the frequency with which each individual visits a particular cell of the cage. The brighter a cell with respect to monkey i 's Heat Map, the more that region is frequented by monkey i . We also have Heat Map's over individual periods of data collection in figures 20(f), 21(e), and 22(e). We have the following observations:

1. The region of the enclosure frequented by monkeys 1 and 2 have a strong overlap. Monkey 1's heat map has its peak intensity on the side of the enclosure away from those of monkeys 3, 4, 5 and 6.
2. Monkeys 5 and 6 also have strong overlapping regions. It is easy to see that monkeys 3, 4, 5 and 6 could form a clique as in figure 18(c) due to large overlap in the Heat Maps .
3. Monkey 6's Heat Map shows activity in the center of the enclosure as well and not just near the walls of the enclosure.

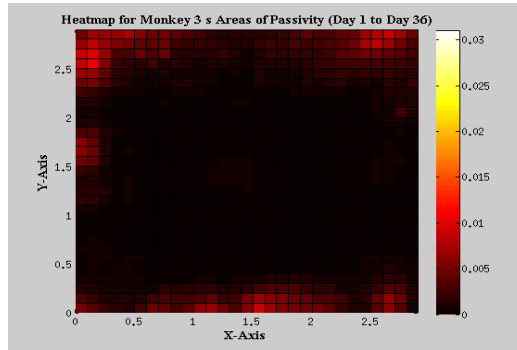
The Heat Maps can also provides an interesting possibility to determine if there are regions associated with low-speed activity like resting and grooming or high speed activity like chasing.



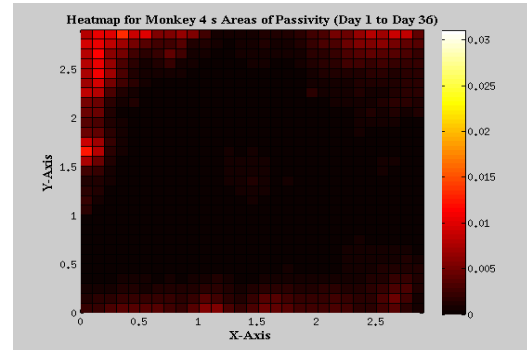
(a) Monkey 1's Heat Map



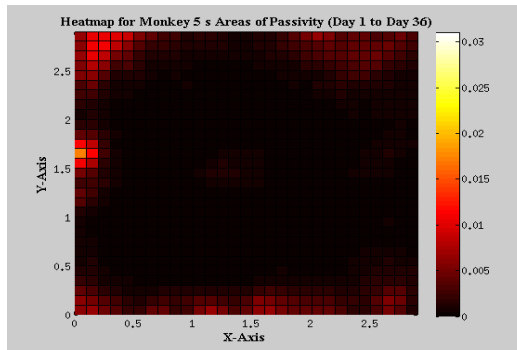
(b) Monkey 2's Heat Map



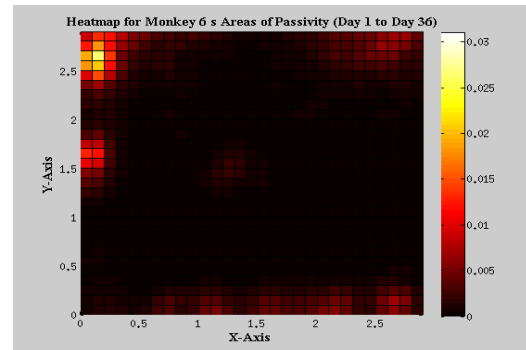
(c) Monkey 3's Heat Map



(d) Monkey 4's Heat Map

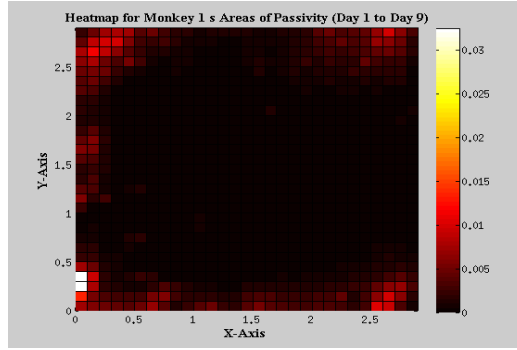


(e) Monkey 5's Heat Map

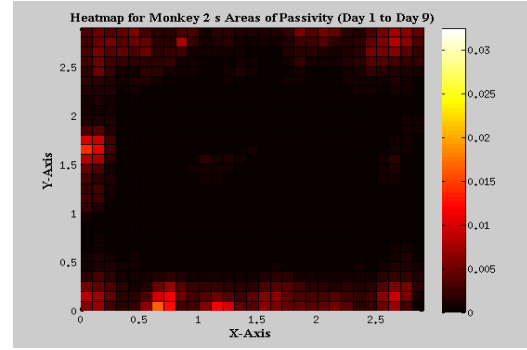


(f) Monkey 6's Heat Map

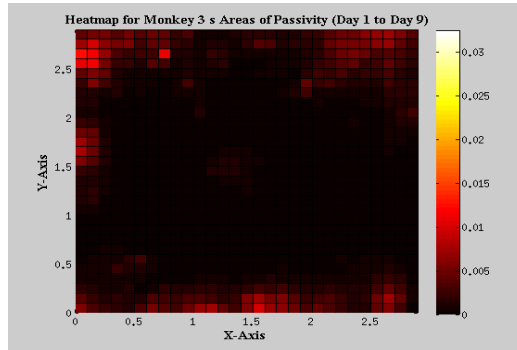
Figure 19: Heat Maps over all 36 days



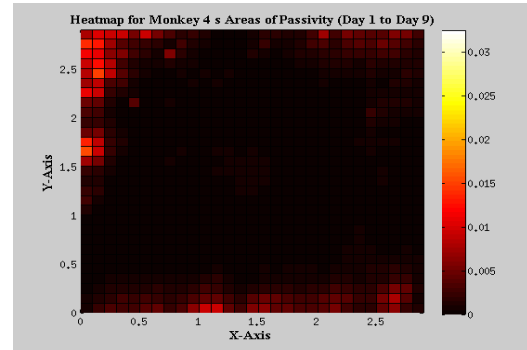
(a) Monkey 1's Heat Map



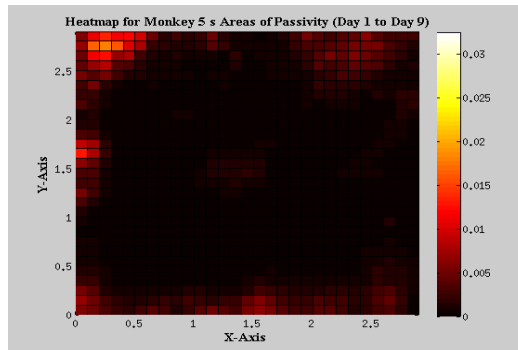
(b) Monkey 2's Heat Map



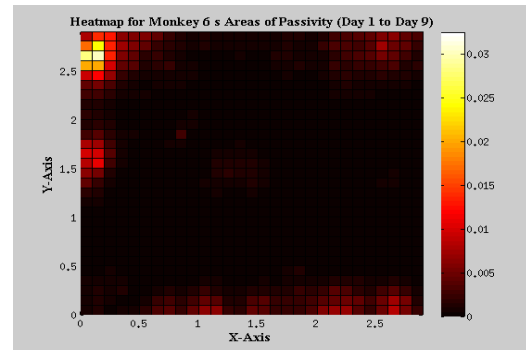
(c) Monkey 3's Heat Map



(d) Monkey 4's Heat Map

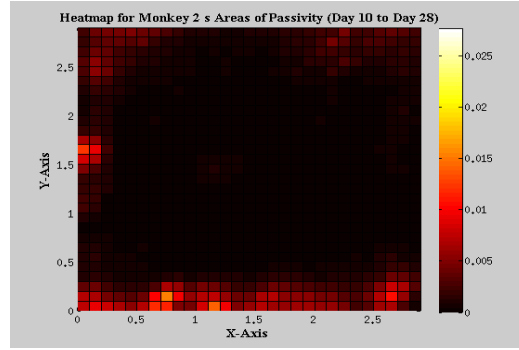


(e) Monkey 5's Heat Map

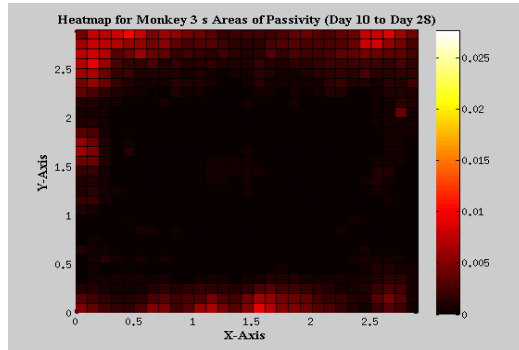


(f) Monkey 6's Heat Map

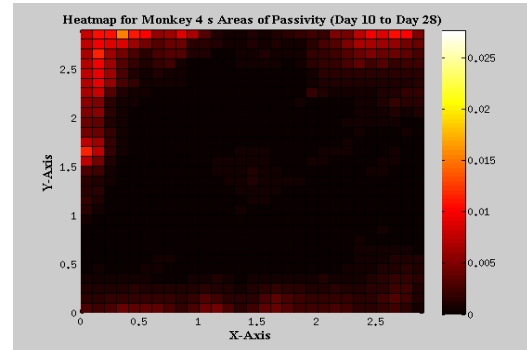
Figure 20: Heat Maps over Period 1



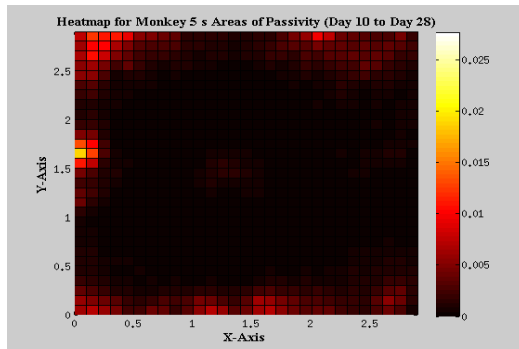
(a) Monkey 2's Heat Map



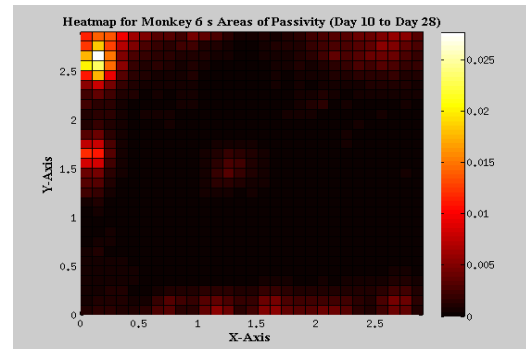
(b) Monkey 3's Heat Map



(c) Monkey 4's Heat Map

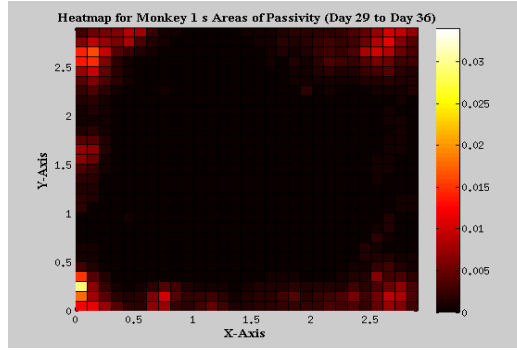


(d) Monkey 5's Heat Map

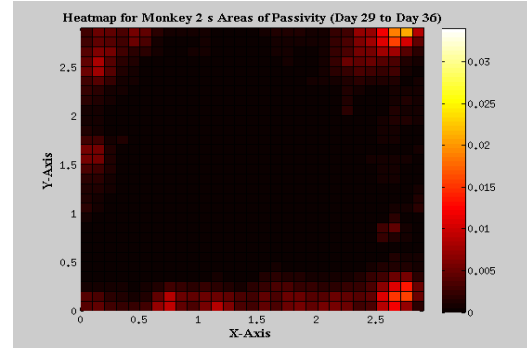


(e) Monkey 6's Heat Map

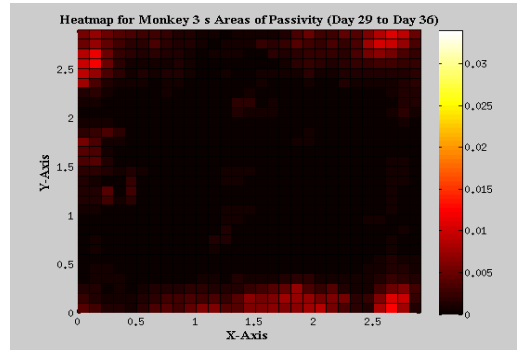
Figure 21: Heat Maps over Period 2 (monkey 1 absent from enclosure)



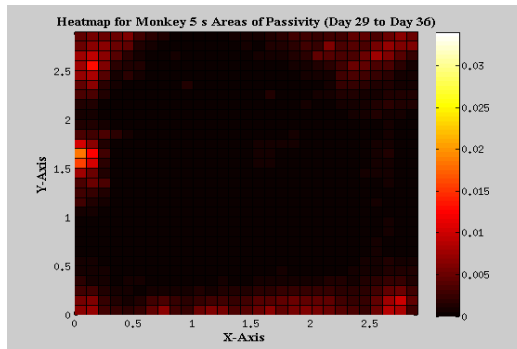
(a) Monkey 1's Heat Map



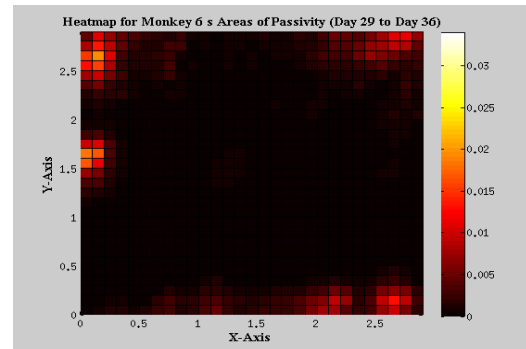
(b) Monkey 2's Heat Map



(c) Monkey 3's Heat Map



(d) Monkey 5's Heat Map



(e) Monkey 6's Heat Map

Figure 22: Heat Maps over Period 3 (monkey 4 data unavailable)

6.3 Dominance Relations

The Hierarchy Matrix H is calculated using equation 2 with a dot product threshold $dp_{thr} = -0.7$ and a speed threshold $dsp_{thr} = 0.9m/s$. This is seen in figure 23. Hierarchy is a directed acyclic graph and therefore linear in nature. However, this constraint of linear hierarchy was not applied during the actual calculation of the Hierarchy matrices. The greater the rank the more dominant a monkey is. The ranks of the nodes of the Hierarchy Graphs in figure 24 are equal to the out-degree. We have the following observations:

1. Period 1 (Days 1 to 9): All monkeys are present during this period. The relative ranks of the monkeys obtained from the data are represented in figure 24(a).

Table 4: Dominance Ranks for Period 1

Dominance Rank	Monkey
1	Monkey 4
2	Monkey 3
3	Monkey 5
4	Monkey 2
5	Monkey 6
6	Monkey 1

2. Period 2 (Days 10 to 28): Monkey 1 is absent in this period and isn't considered.

The relative ranks of the monkeys obtained from the data are:

Table 5: Dominance Ranks for Period 2

Dominance Rank	Monkey
1	Monkey 4
2	Monkey 3
3	Monkey 5
4	Monkey 2
5	Monkey 6

We see that the structure obtained for period 1 has been preserved in period 2 (as seen in figure 24(b)) even when the group does not include monkey 1.

3. Period 3 (Days 29 to 36) : Data for monkey 4 for this period is unavailable and it is considered to be absent from the group. The relative ranks of the monkeys obtained from the data are:

Table 6: Dominance Ranks for Period 3

Dominance Rank	Monkey
1	Monkey 3
2	Monkey 5
3	Monkey 6
4	Monkey 2
5	Monkey 1

We see that the structure obtained for period 3 as seen in figure 24(c) is similar to that obtained for periods 1 and 2. The only change is in the ordering of monkeys 2 and 6.

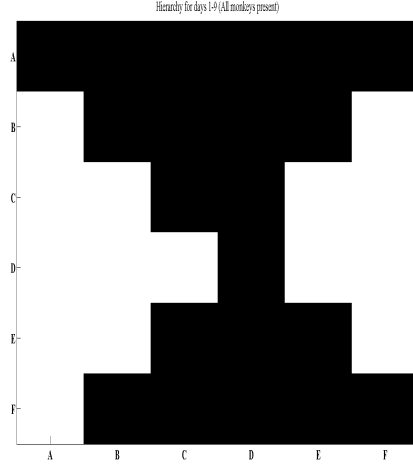
The Hierarchy for Periods 1,2, and 3 as well as the overall Hierarchy for the 36 days matches our assumption of a linear structure for rhesus macaques. This is seen in figure 25(b). The relative rank structure is

Table 7: Overall Dominance Ranks

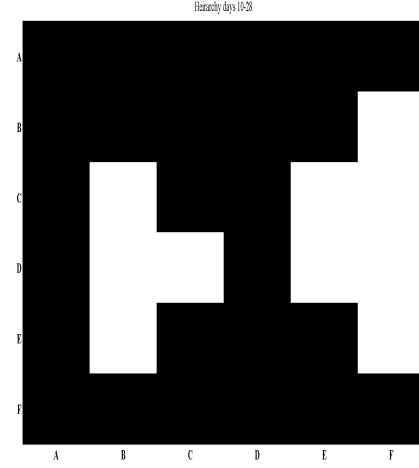
Dominance Rank	Monkey
1	Monkey 4
2	Monkey 3
3	Monkey 5
4	Monkey 2
5	Monkey 6
6	Monkey 1

It is important to note that monkey 1 was removed from the enclosure due to ill health during period 2 of data collection. The data itself may be biased against

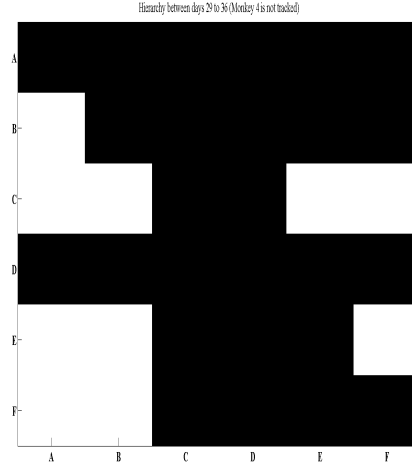
monkey 1 to indicate a low rank. But another way of looking at it would be that monkey 1 doesn't produce too many displacements or withdrawals as it was injured in a lost fight with another monkey.



(a) Hierarchy Matrix H over period 1

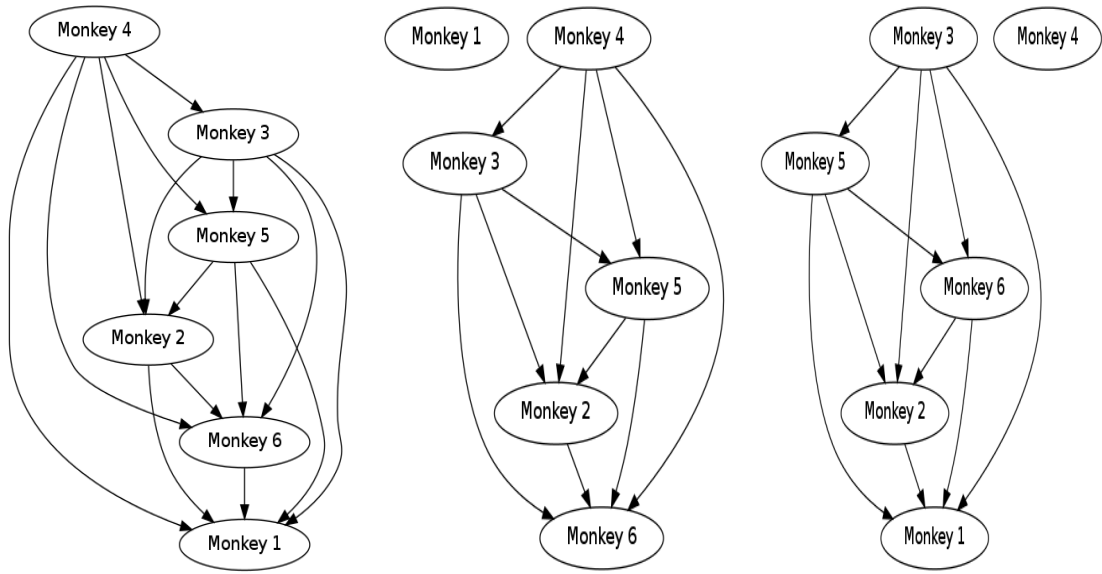


(b) Hierarchy Matrix H over period 2 (Monkey 1's data unavailable)



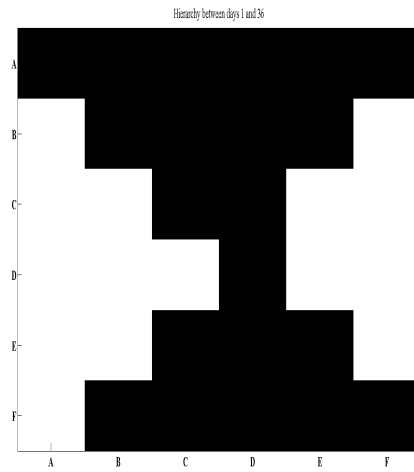
(c) Hierarchy Matrix H over period 3 (Monkey 4's data unavailable)

Figure 23: Inferred Hierarchy Matrices over individual periods

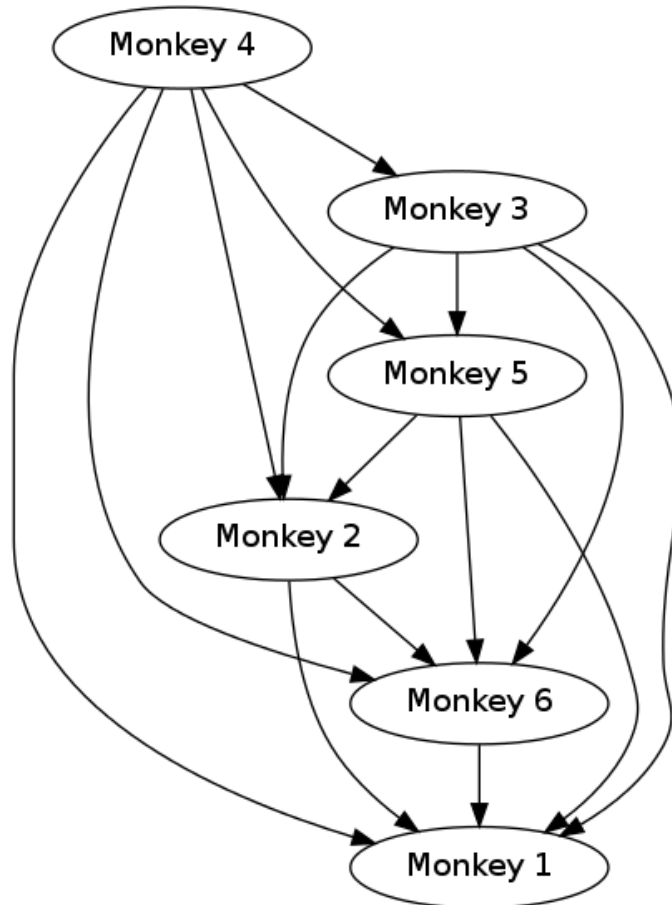


(a) Hierarchy Graph over period 1
 (b) Hierarchy Graph over period 2 (Monkey 1 data unavailable)
 (c) Hierarchy Graph over period 3 (Monkey 4 data unavailable)

Figure 24: Inferred Hierarchy Graphs over individual periods



(a) Overall Hierarchy Matrix H



(b) Overall Hierarchy Graph

Figure 25: Inferred overall Hierarchy data

CHAPTER VII

CONCLUSION

The objective of this work was the automatic inference of group social structure among rhesus macaques. This structure was represented in the form of Affiliation Graphs, Heat Maps, and Hierarchy Graphs that were obtained from the Radio-Frequency Identification position tracking dataset of 36 days. Three periods of data collection over which the group composition changes gradually have also been considered in the approach. The inferred affiliation and dominance relations show features that are robust to short term changes in group composition as expected of a stable social structure. A comparison of the ground truth for live animals with the experimental results being currently unavailable, the performance of the approach described in this Thesis has been validated using a simulated monkey behavior model SMALLDOM-WORLD [11]. The model was developed with inputs from primatologists at Yerkes National Primate Research Center and provides an accurate representation of rhesus macaque spatial behavior. The results from the simulations are encouraging as the recovered hierarchy and association preferences have been shown to significantly match the ground truth.

One of the visible drawbacks of working in the spatial domain alone is the loss of resolution with which we can differentiate between playful and agonistic behaviors. For example, chasing in the context of a time series of positions can be classified as either play or agonistic behavior. As a consideration for future work, rhesus macaques use a rich variety of visual and auditory social gestures such as yawning, lip smacking, grimacing, roaring, grunting, and squeaking. Through an additional video or audio

input, the information from these sources can be combined with the approach presented in this work to provide a more detailed representation of social structure that can capture complex behaviors. The goal of future work would also be to incorporate a more general probabilistic framework to improve inferred social structure.

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